Leonardo ENERGY

An initiative by

International Copper Association Europe

Electrification Academy

RAP

OST Eastern Switzerland University of Applied Sciences

IES Institute for Energy Systems

A clean industrial era: Market, technology, and application potentials of high-temperature heat pumps

December 4, 2024, 10:00 – 11:00 CET

Dr. Cordin Arpagaus
cordin.arpagaus@ost.ch
Tel. +41 81 377 94 34

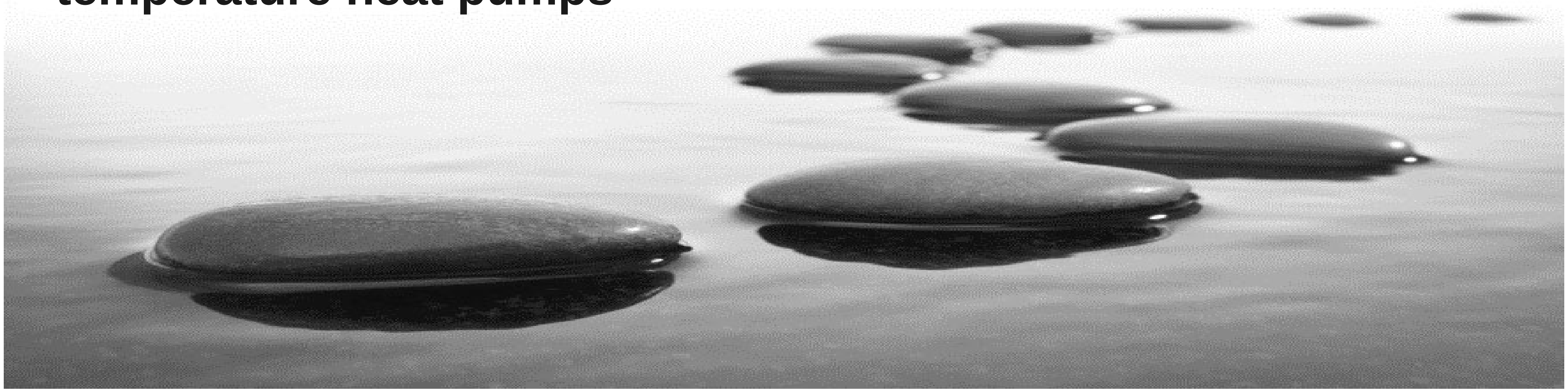
Institute for Energy Systems IES
www.ost.ch/ies

Co-Authors:

- Dr. Frédéric Bless
- Dr. Sidharth Paranjape
- Leon Brendel, PhD
- Michael Uhlmann
- Prof. Stefan Bertsch, PhD

Content

- A market overview of high-temperature heat pump suppliers
- Insight into the limitations and state of current technology
- Potential applications for steam generation
- Three key recommendations for broader market adoption of high-temperature heat pumps



cordin.arpagaus@ost.ch

Introduction – OST IES – Where we are

Heat pump test center (WPZ) at OST in Buchs, Switzerland

cordin.arpagaus@ost.ch

Introduction – Our competences

IES | Institute for Energy Systems

OST Eastern Switzerland University of Applied Sciences

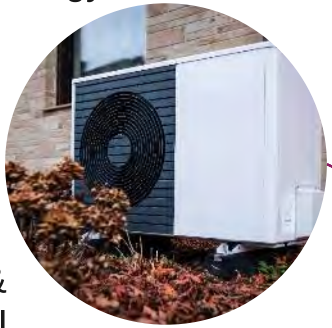
«Engineering a Net Zero Future that Works»

Heat Pump & Refrigeration Technology

Accredited Heat Pump Test Center

Heat Pump Field Tests

Heat Pump & HVAC Control



Residential

Photovoltaics

Decentralized Energy Supply

Grids (Electrical and Thermal)

Energy Supply

Industrial Heat Pumps

Energy Analysis

Efficiency Optimization

Industry

IES | Institute for Energy Systems

Power Electronics

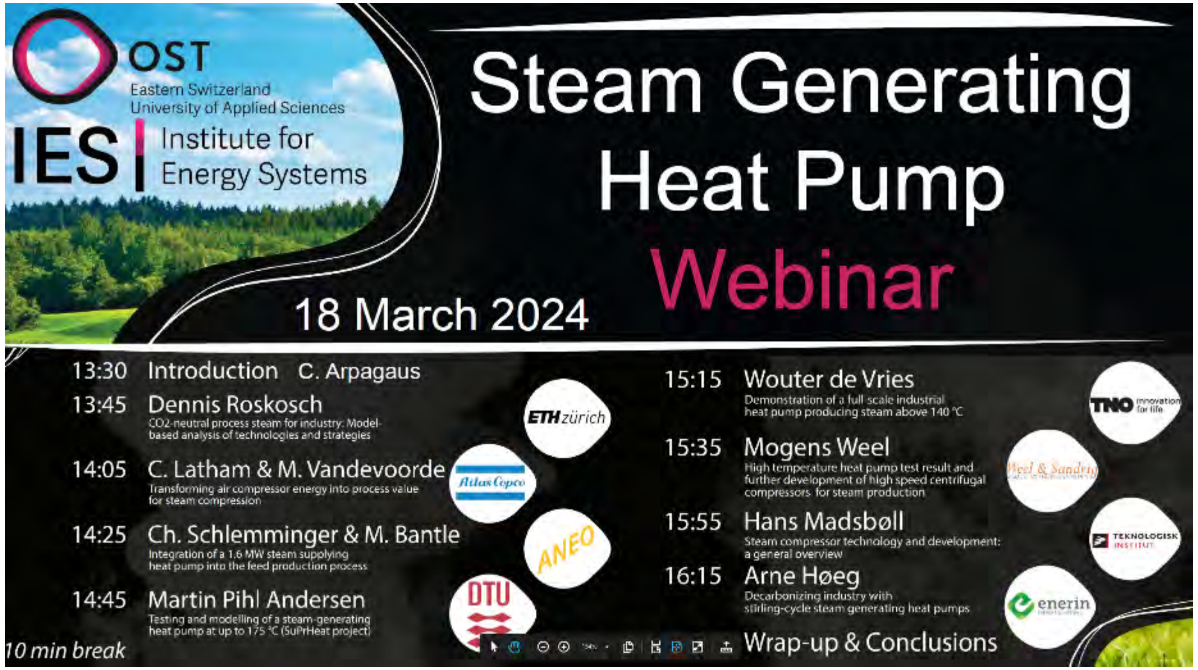
Thermal Management

Test Bench Development

Mobility

cordin.arpagaus@ost.ch

OST Webinar on 18 March 2024

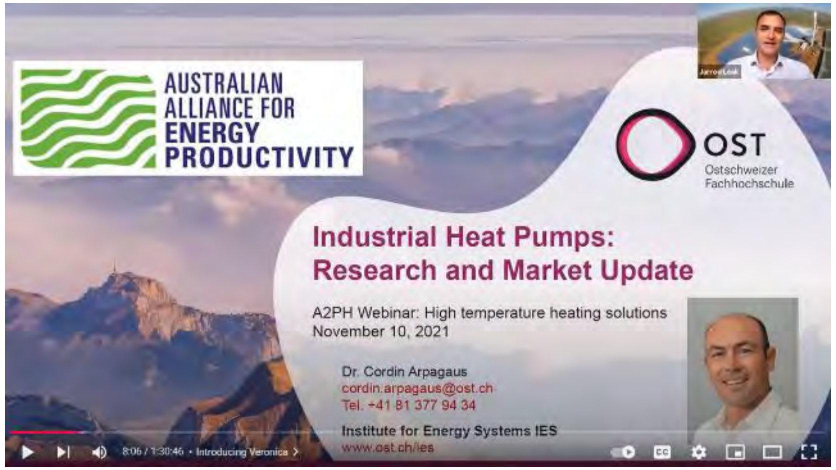


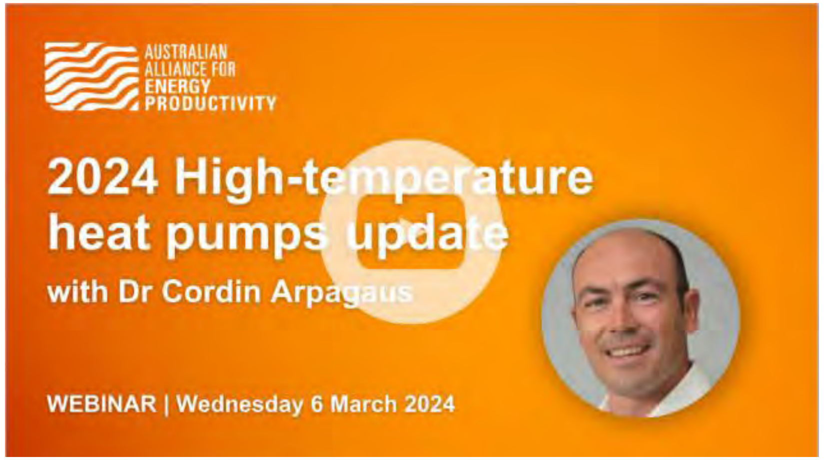
- **Webinar with 540 registrations !**
- **Participants from 42 countries !**

- **Recordings on YouTube:**
  [Steam Generating Heat Pumps Webinar 2024 – YouTube]
- **Download PDF Presentations:**
  [Webinar on Steam Generating Heat Pumps: SWEET DeCarbCH (sweet-decarb.ch)]

cordin.arpagaus@ost.ch
OST

Introduction – Available Webinar Recordings on High-Temperature Heat Pumps



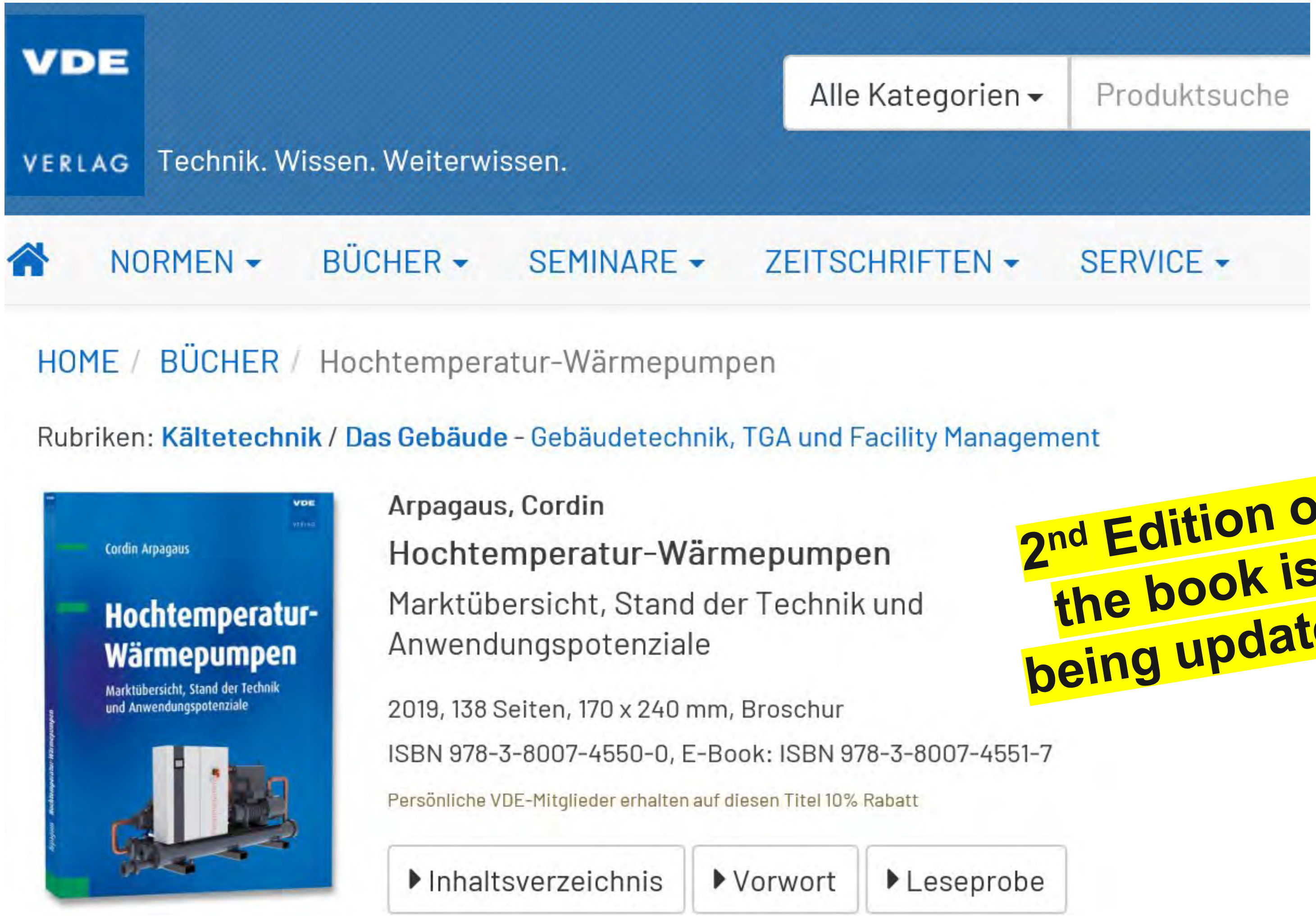


Recording: 2021	Recording: 2023	Recording: 2024
10 November 2021 (4’100 views)	22 February 2023 (8’100 views)	6 March 2024 (1’900 views)

cordin.arpagaus@ost.ch

Introduction – Self-promotion

Book «Hochtemperatur-Wärmepumpen»



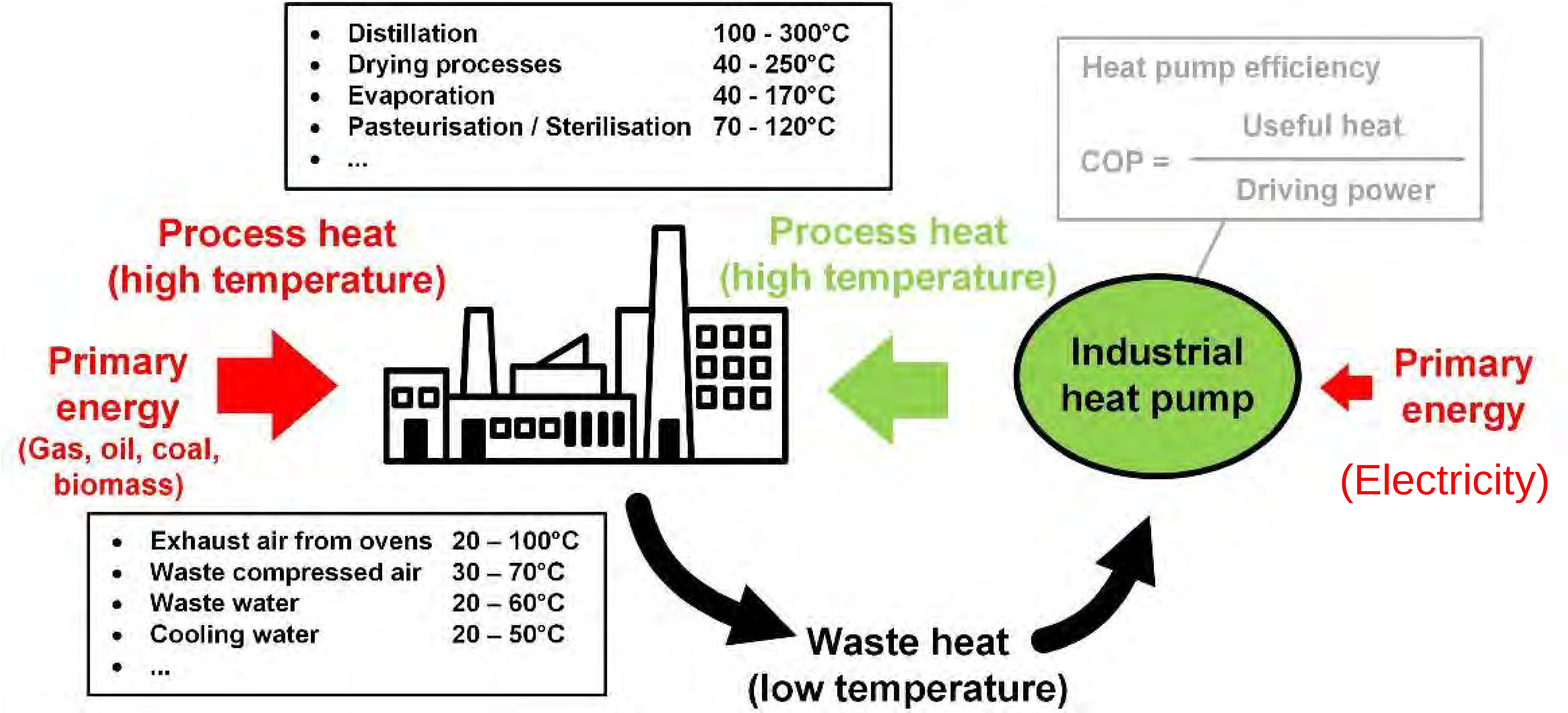
2nd Edition of the book is being updated

Link: https://www.vde-verlag.de/buecher/494550/hochtemperatur-waermepumpen.html

cordin.arpagaus@ost.ch

Motivation

Industrial Heat Pumps for Waste Heat Recovery

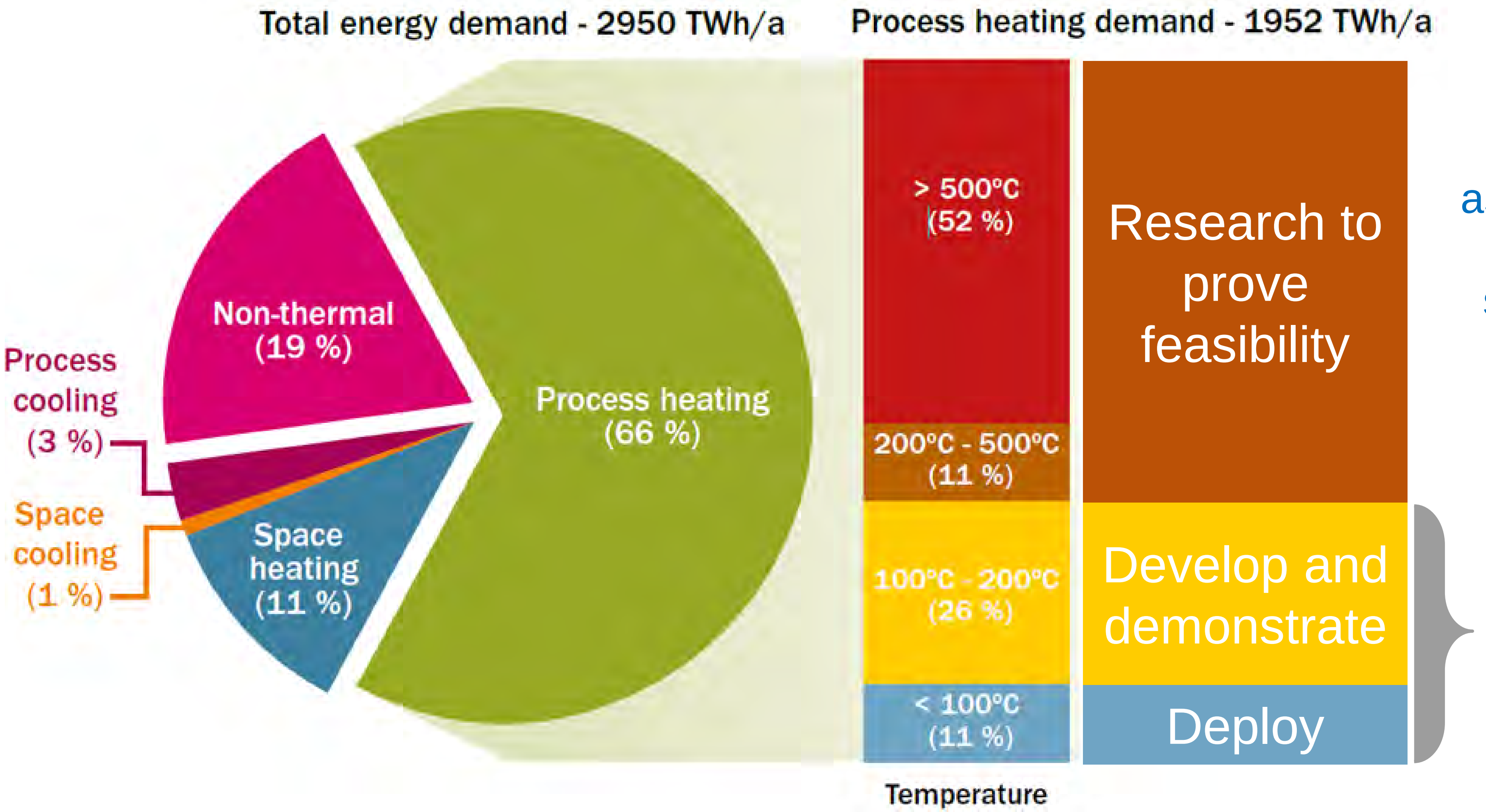


Source: Arpagaus et al. (2021): Industrial Heat Pumps – Research and Market, DeCarbCH Lunch Talk, November 9, 2021

cordin.arpagaus@ost.ch

Motivation

Process Heat Demand in the European Industry



Heat pumps are identified as a **key technology for the decarbonization** of this share of the industrial heat supply (< 200 °C)

37% of process heat of European industry is < 200 ºC (730 TWh/a)

Source: De Boer et al. (2020): White Paper, Strengthening Industrial Heat Pump Innovation, Decarbonizing Industrial Heat

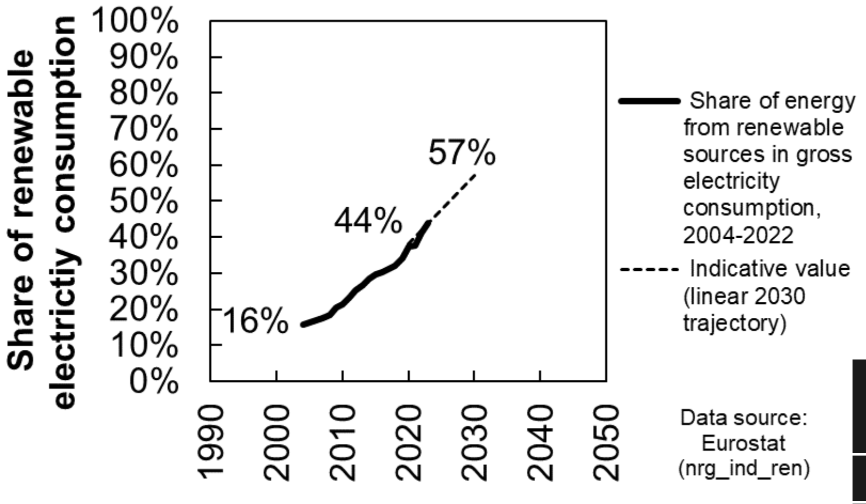
cordin.arpagaus@ost.ch

Motivation – Renewable electricity reduces CO_2 emission factor

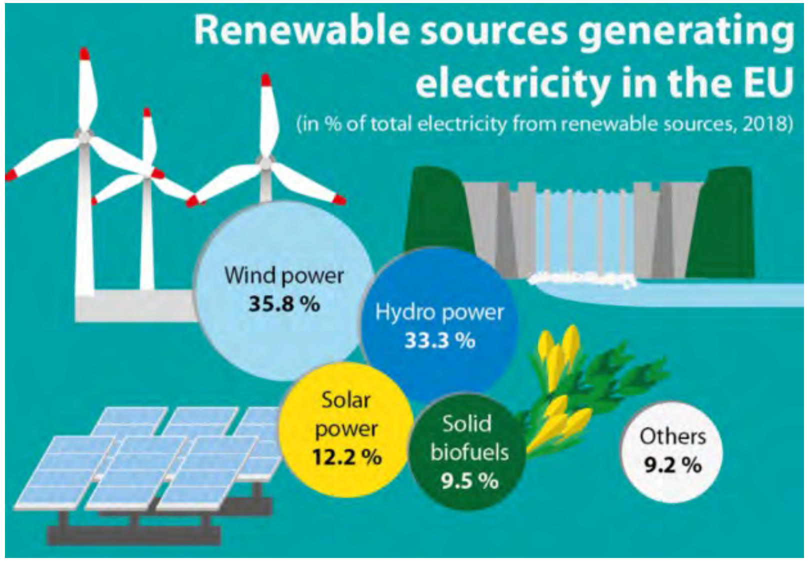
Electricity from renewable sources up to 44% in 2023

EU level (EU-27)

Share of energy from renewable sources in gross electricity consumption



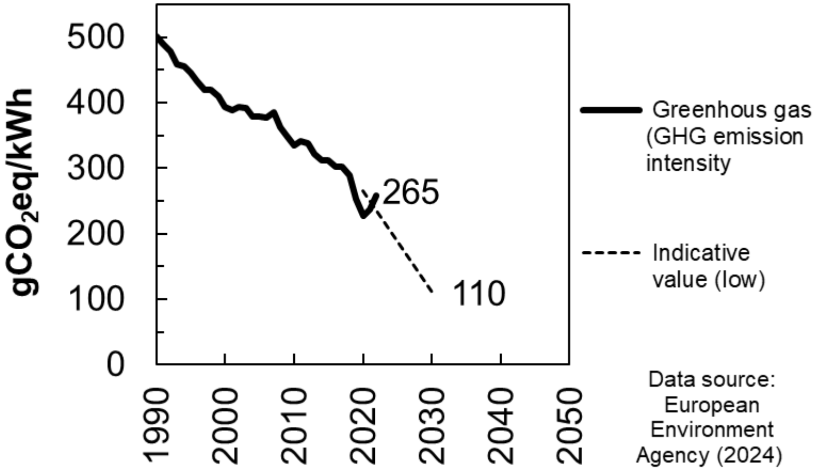
Data source: Eurostat (2024): Share of energy from renewable sources, data code nrg_ind_ren, https://doi.org/10.2908/nrg_ind_ren



% of total electricity from renewable sources	2018	2022
Wind	35.8%	**37.5%**
Solar	12.2%	**18.2%**
Hydro	33.3%	29.9%
Solid biofuels	9.5%	6.9%
Others	9.2%	7.5%

Data source: Eurostat Renewable energy statistics

Greenhouse gas (GHG) emission intensity of electricity generation



Data source: European Environment Agency (2024): Greenhouse gas emission intensity of electricity generation in Europe, 14 Jun 2024

cordin.arpagaus@ost.ch

Steam = important energy carrier in the industry

STEAM

Evaporation is an energy-intensive unit operation

Heating of water from 20 °C to 100 °C
= 330 kJ/kg
→ 1 t/h water = 90 kW

Evaporation of water
= 2’300 kJ/kg
→ 1t/h water = 630 kW

7 x more energy

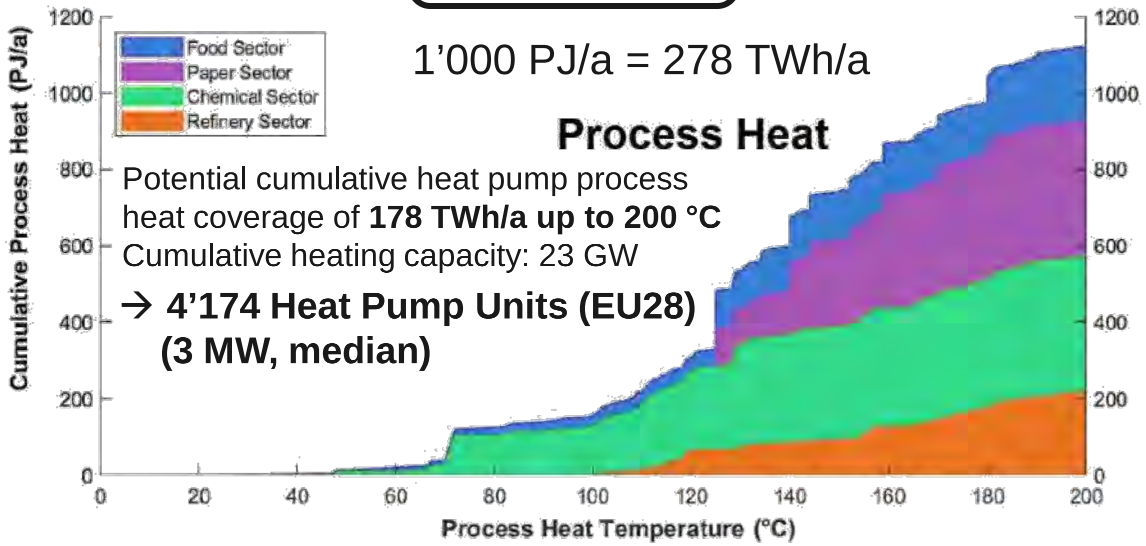
iStock ID:104659952

Application Potential up to 200 °C is large … but still emerging

Industrial process heat demand

EU28

1’000 PJ/a = 278 TWh/a



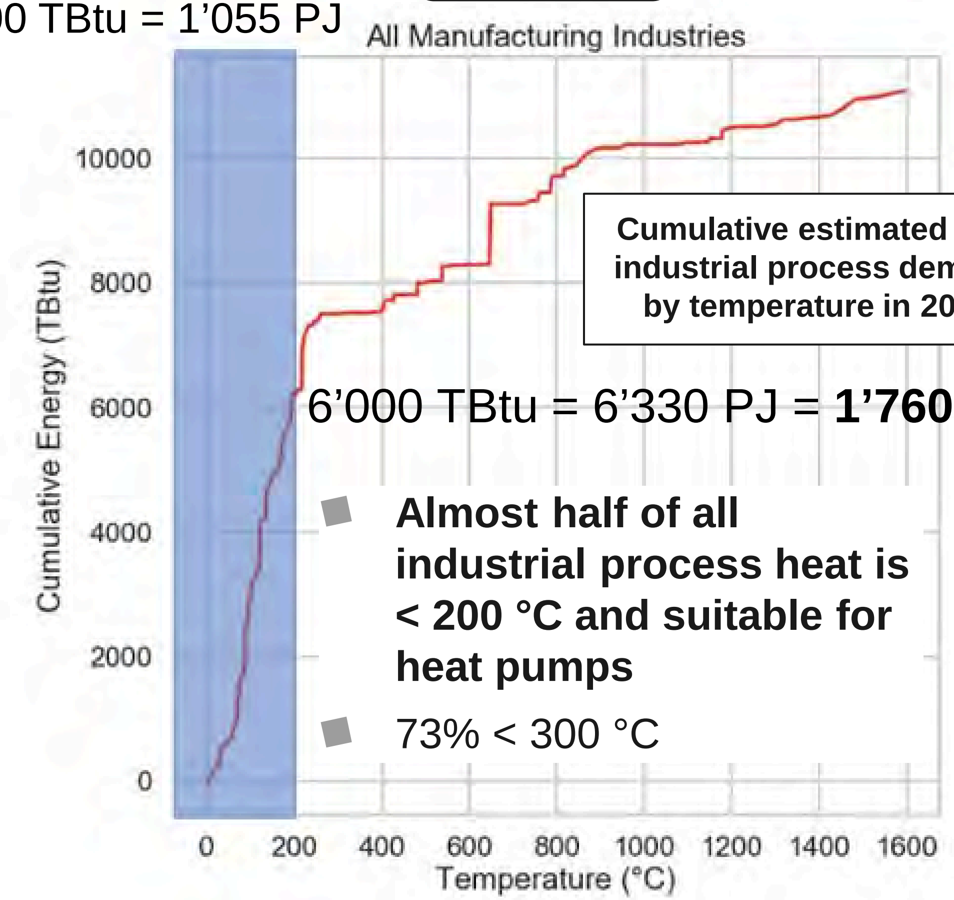
Potential cumulative heat pump process heat coverage of **178 TWh/a up to 200 °C**
Cumulative heating capacity: 23 GW

→ **4’174 Heat Pump Units (EU28) (3 MW, median)**

- Highest potential in the **food, paper, and chemical sectors**
- Available **waste heat** between 40 °C and 100 ºC is estimated to be 212 TWh/a (764 PJ/a) (EU28)

U.S.

1’000 TBtu = 1’055 PJ



Cumulative estimated U.S. industrial process demand by temperature in 2014

6’000 TBtu = 6’330 PJ = **1’760 TWh**

- **Almost half of all industrial process heat is < 200 °C and suitable for heat pumps**
- 73% < 300 °C

Source: Marina et al. (2021): An estimation of the European industrial heat pump market potential, Renewable and Sustainable Energy Reviews, 139, 110545, https://doi.org/10.1016/j.rser.2020.110545

Source: McMillan et al. (2021): Opportunities for Solar Industrial Process Heat in the United States, Technical Report, NREL/TP-6A20-77760, https://www.nrel.gov/docs/fy21osti/77760.pdf

cordin.arpagaus@ost.ch

Application Potential in Europe EU-28

Process heat demand, temperature levels, industrial sectors

EU28

	Heat Consumption (TWh/a)	EU-28	
	Space heating	297	16%
	Hot water	25	1%
Process heat	PH <60 °C	55	3%
Process heat	PH 60 to 80 °C	53	3%
Process heat	PH 80 to 100 °C	**89**	**5%**
Process heat	PH 100 to 150 °C	**192**	**11%**
Process heat	PH 150 to 200 °C	**80**	**4%**
Process heat	PH 200 to 500 °C	151	8%
Process heat	PH 500 to 1'000 °C	376	21%
Process heat	PH >1'000 °C	504	28%
	Total Heat Consumption (TWh/year)	1'821	100%
	Total Process Heat <60 °C to >1'000 °C (TWh/year)	1'499	
	Total Process Heat 90 °C to 160 °C (TWh/year)	**237**	**16%**

Process Heat Consumption (TWh/a)		
Industrial sector	**PH 100 to 150 °C**	**PH 150 to 200 °C**
Iron and steel	19.8	7.3
Chemical	19.3	15.4
Non-ferrous metal	2.7	1.0
Non-metallic minerals	36.5	0.0
Food and tobacco	68.0	8.8
Paper, pulp and print	10.0	39.4
Machinery	6.9	2.9
Wood and wood products	0.2	0.7
Transport equipment	1.2	0.2
Textile and leather	6.9	0.0
Other	19.1	4.2
Total	**191**	**80**

Data source: Kosmadakis (2019): Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries, Applied Thermal Engineering, 156, 287-298, https://doi.org/10.1016/j.applthermaleng.2019.04.082

cordin.arpagaus@ost.ch

Application Potential

Temperature levels of industrial processes

Sector	Process	Temperature [°C]
Paper	Drying	90 -240
	Boiling	110 - 180
	Bleaching	40 - 150
	De-inking	50 - 70
Food & beverages	Drying	40 - 250
	Evaporation	40 - 170
	Pasteurization	60 - 150
	Sterilization	100 - 140
	Boiling	70 - 120
	Distillation	40 - 100
	Blanching	60 - 90
	Scalding	50 - 90
	Concentration	60 - 80
	Tempering	40 - 80
	Smoking	20 - 80
Chemicals	Destillation	100 - 300
	Compression	110 - 170
	Thermoforming	130 - 160
	Concentration	120 - 140
	Boiling	80 - 110
	Bioreactions	20 - 60
Automotive	Resin molding	70 - 130
Metal	Drying	60 - 200
	Pickling	20 - 100
	Degreasing	20 - 100
	Electroplating	30 - 90
	Phosphating	30 - 90
	Chromating	20 - 80
	Purging	40 - 70

Sector	Process	Temperature [°C]
Plastic	Injection modling	90 - 300
	Pellets drying	40 - 150
	Preheating	50 - 70
Mechanical engineering	Surface treatment	20 - 120
	Cleaning	40 -90
Textiles	Coloring	40 - 160
	Drying	60 - 130
	Washing	40 - 110
	Bleaching	40 - 100
Wood	Glueing	120 - 180
	Pressing	120 - 170
	Drying	40 - 150
	Steaming	70 - 100
	Cocking	80 - 90
	Staining	50 - 80
	Pickling	40 - 70
Several sectors	Hot water	20 - 110
	Preheating	20 - 100
	Washing/Cleaning	30 - 90
	Space heating	20 - 80

Technology Readiness Level (TRL):

- conventional HP < 80°C, established in industry
- commercial available HP 80 - 100°C, key technology
- prototype status, technology development, HTHP 100 - 140°C
- laboratory research, functional models, proof of concept, VHTHP > 140°C

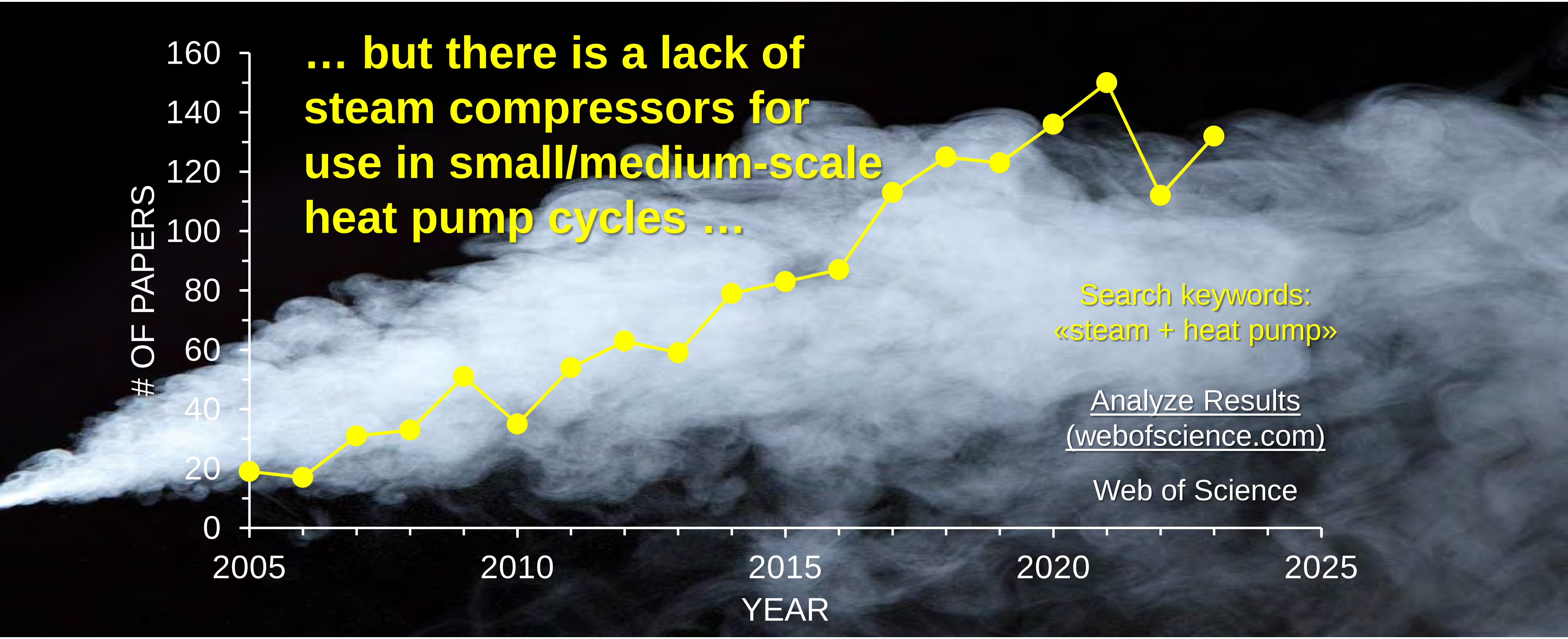
Source: Arpagaus et al. (2018): Review on High-Temperature Heat Pumps, https://doi.org/10.1016/j.energy.2018.03.166

OST

cordin.arpagaus@ost.ch

STEAM

Publications are increasing

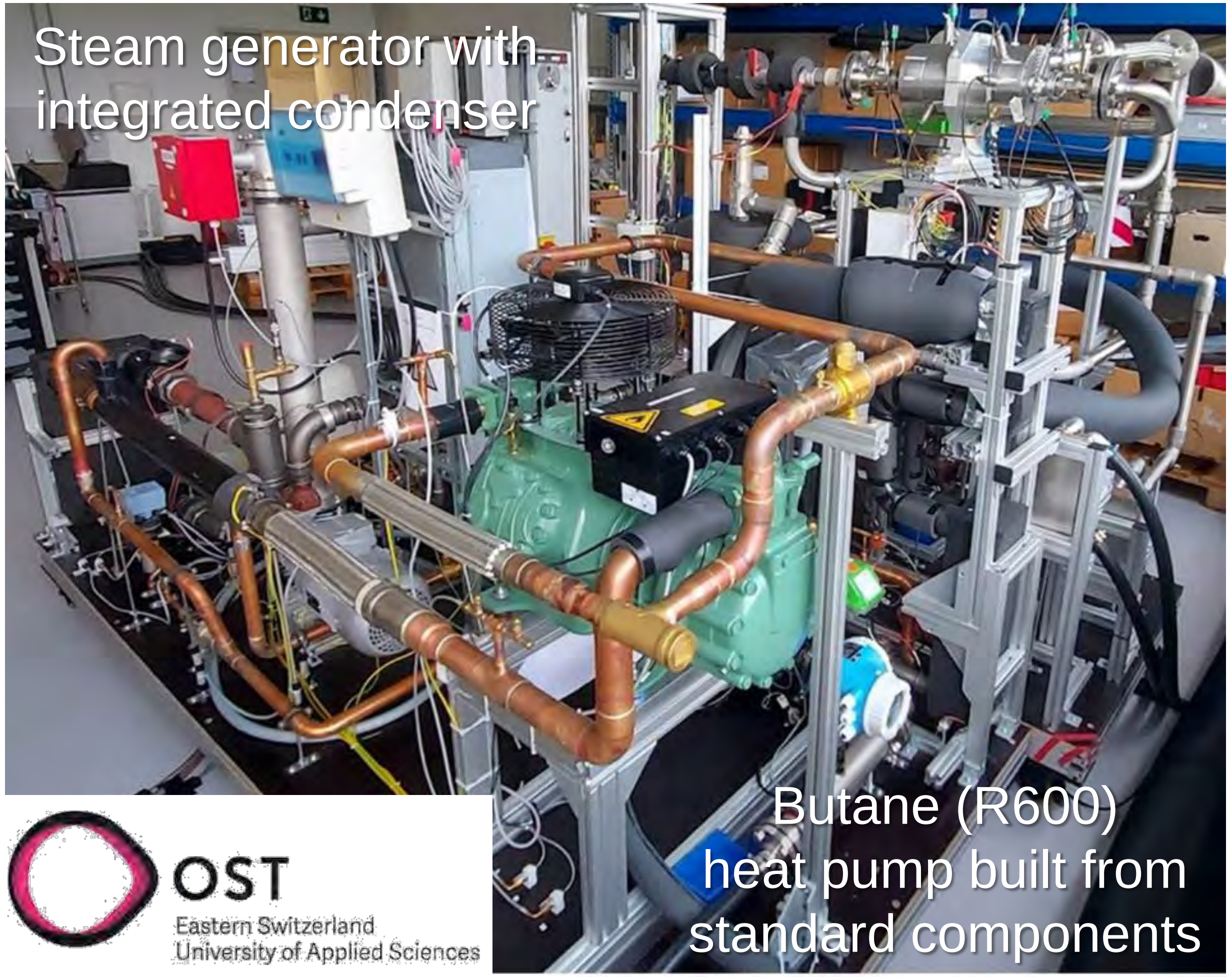


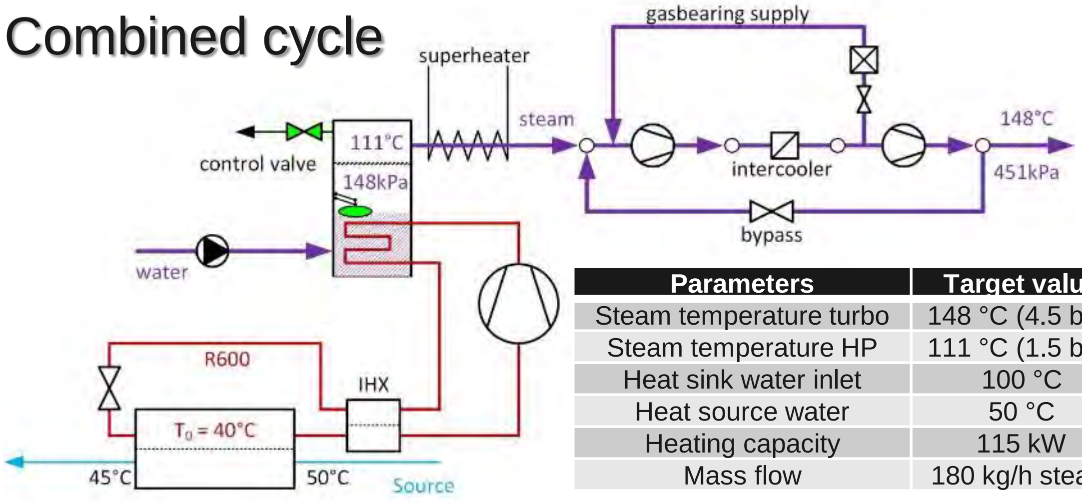
cordin.arpagaus@ost.ch

OST

Ongoing development at OST – Efficient steam generation in industry, Innosuisse (42533.1 IP-EE)

R600/R718 (Butane/Water) Steam generating heat pump





Parameters	Target value
Steam temperature turbo	148 °C (4.5 bar)
Steam temperature HP	111 °C (1.5 bar)
Heat sink water inlet	100 °C
Heat source water	50 °C
Heating capacity	115 kW
Mass flow	180 kg/h steam

Source: Uhlmann, M., Olmedo, L.E., Arpagaus, C., Bless, F., Schiffmann, J., Bertsch, S.: Efficient steam generation in industry – Combined heat pump cycle with mechanical vapor recompression, 15th IIR-Gustav Lorentzen conference on Natural Refrigerants, June 13-15, 2022, Trondheim, Norway, http://dx.doi.org/10.18462/iir.gl2022.0049

cordin.arpagaus@ost.ch

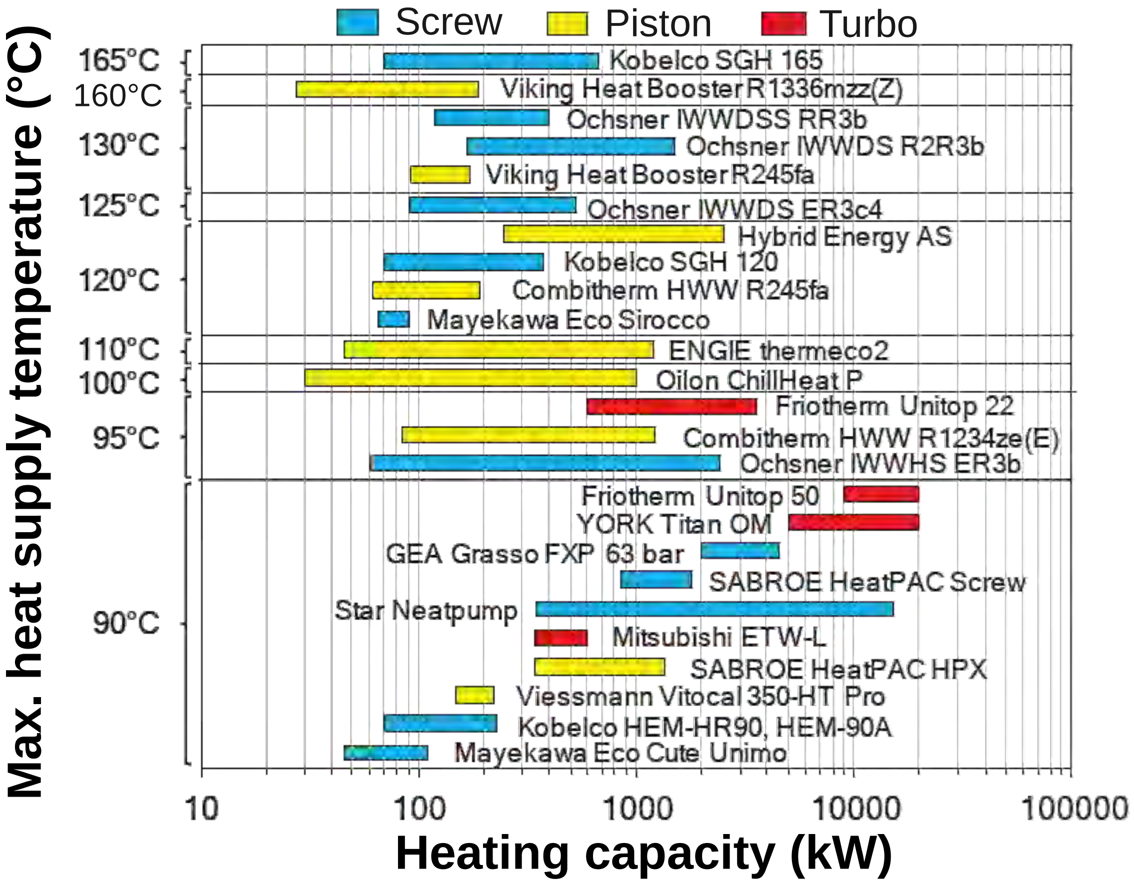
Suppliers of High-Temperature Heat Pumps

Evolution of the HTHP market

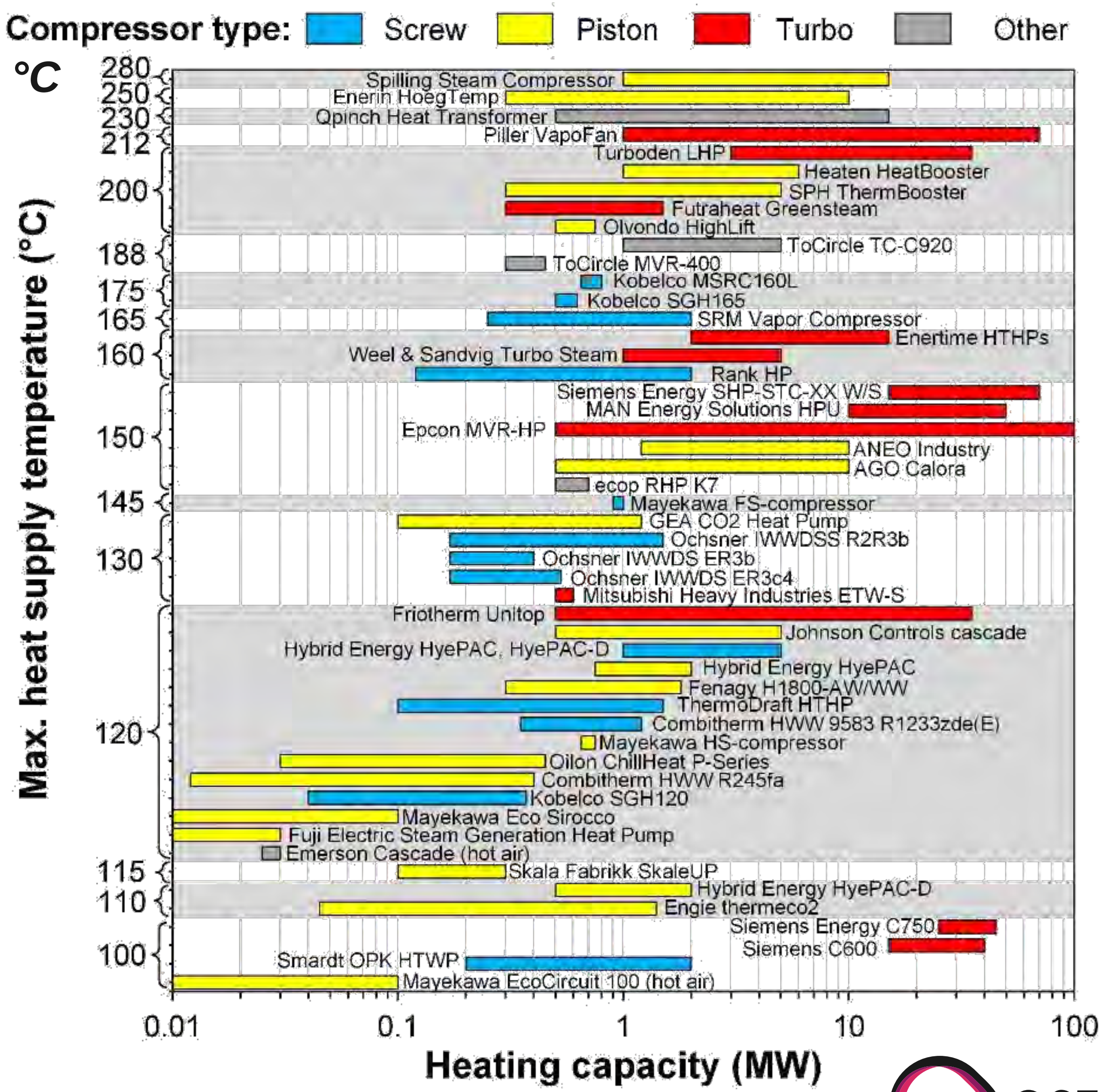
2018

25 HTHPs > 90 °C

50 HTHPs > 100 °C

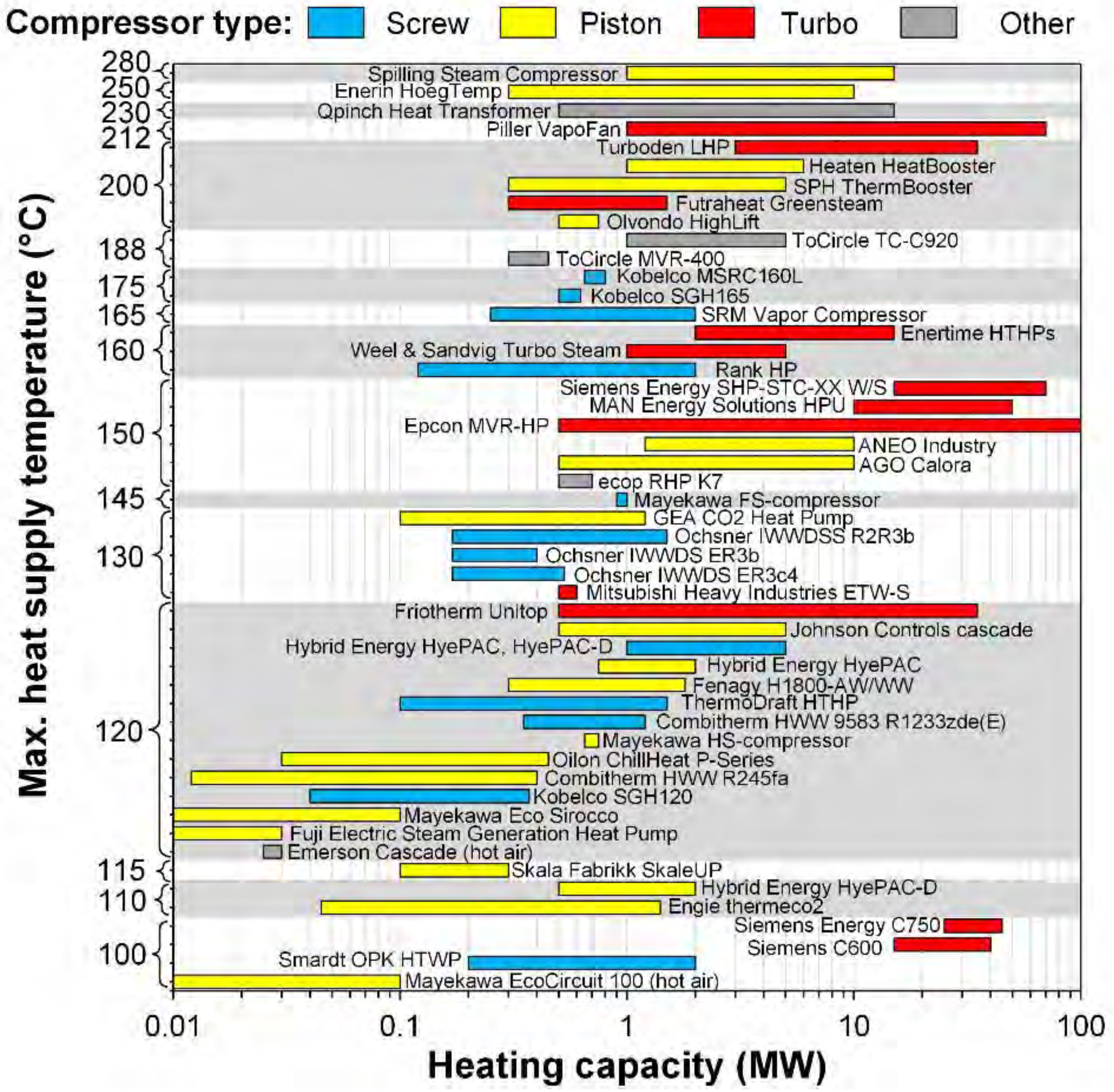


2024



cordin.arpagaus@ost.ch

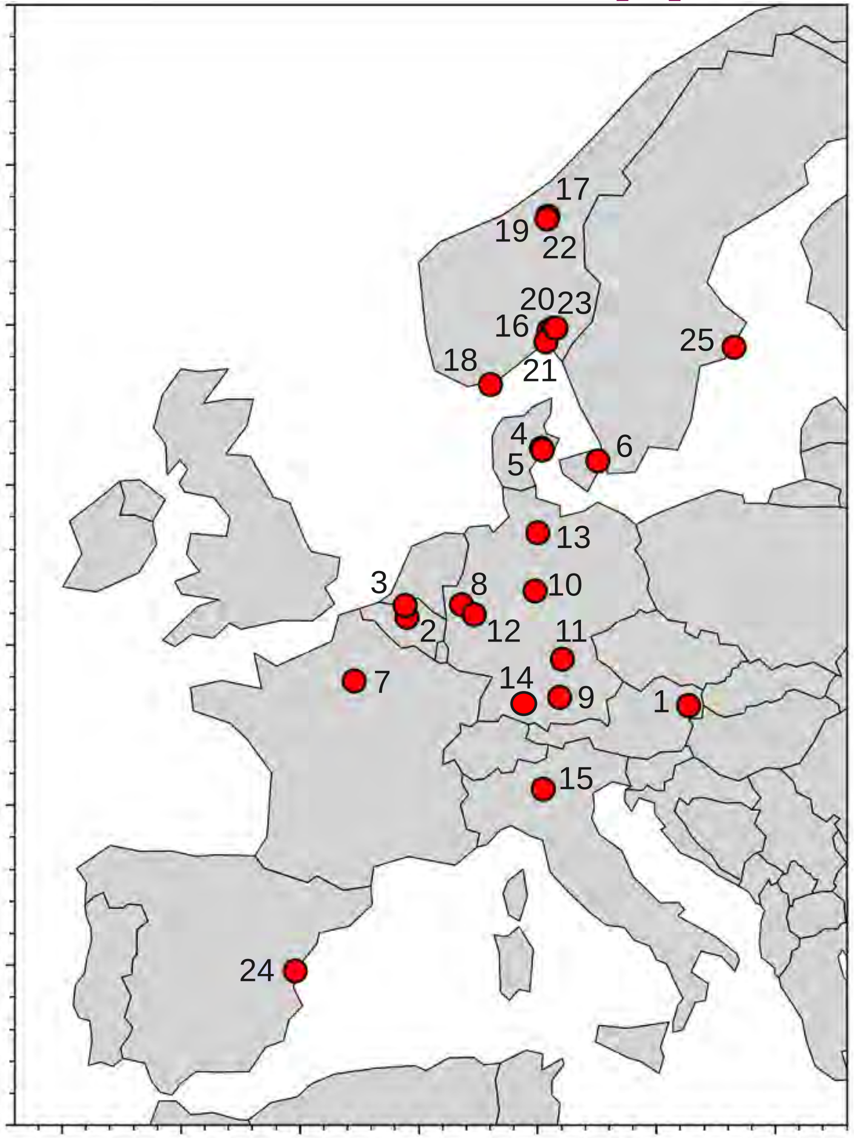
Suppliers of HTHP technology above 100 °C (non-exhaustive list)



cordin.arpagaus@ost.ch

OST

Headquarters of HTHP suppliers in Europe



1	Ecop (AT)
2	Mayekawa MYCOM (BE)
3	Qpinch (BE)
4	Fenagy (DK)
5	Johnson Controls (DK)
6	Weel and Sandvig (DK)
7	Enertime (FR)
8	GEA (DE)
9	MAN (DE)
10	Piller (DE)
11	Siemens (DE)
12	SPH (DE)
13	Spilling (DE)
14	Combitherm (DE)
15	Turboden (IT)
16	Enerin (NO)
17	Epcon (NO)
18	Heaten (NO)
19	Hybrid Energy (NO)
20	ANEO (NO)
21	Olvondo (NO)
22	Skala Fabrikk (NO)
23	ToCircle (NO)
24	Rank (ES)
25	SRM (SE)

Japan

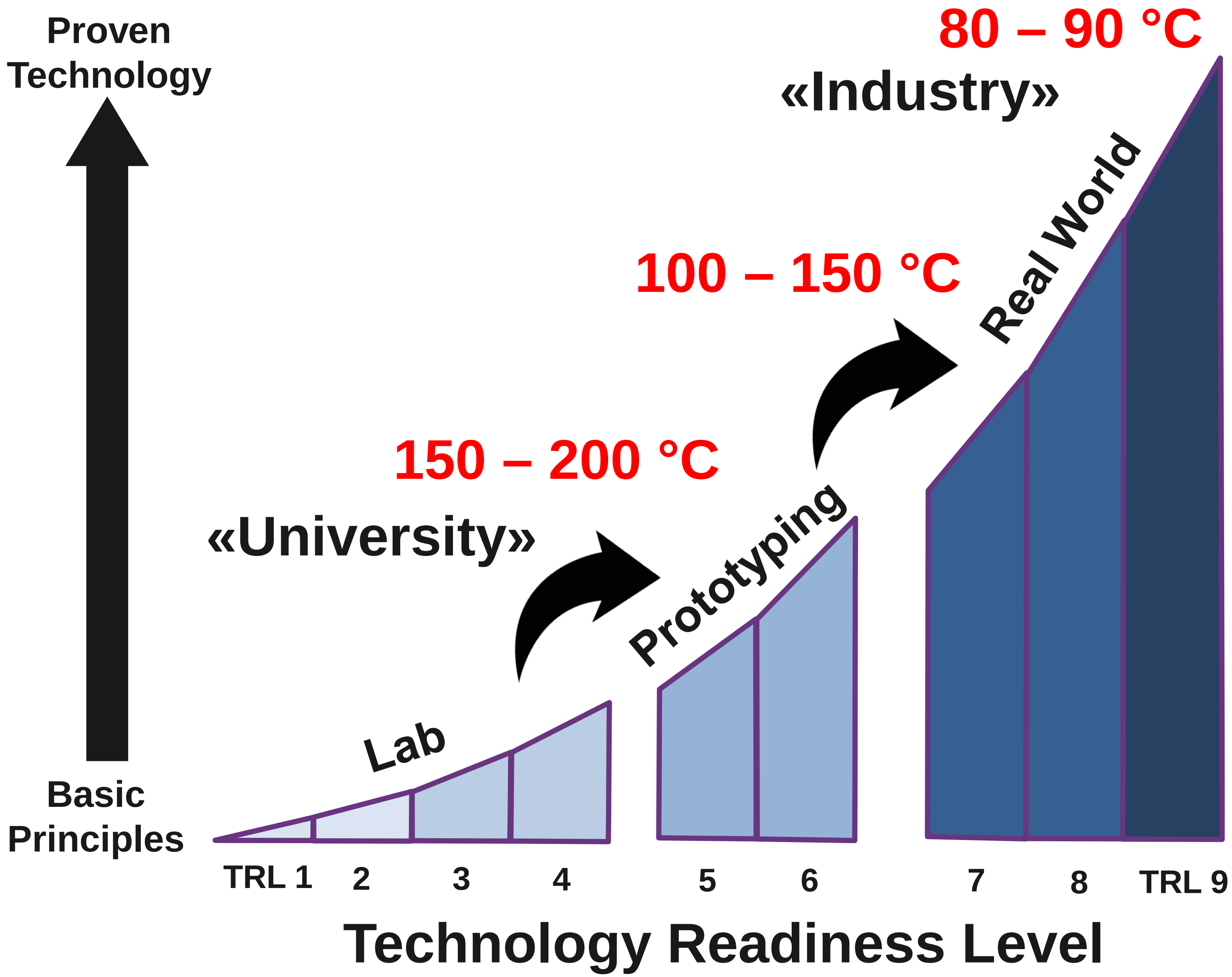
26	Fuji (JP)
27	KOBELCO (JP)
28	Mitsubishi (JP)

Based on database of IEA HPT Annex 58:

https://heatpumpingtechnologies.org/annex58/task1

cordin.arpagaus@ost.ch

What is the Technology Readiness Level (TRL) of HTHP ?



Technology Readiness Levels (TRL)	
TRL 9	Actual system proven in operational environment
TRL 8	System complete and qualified
TRL 7	System prototype demonstration in operational environment
TRL 6	Technology demonstrated in relevant (industrial) environment
TRL 5	Technology validated in relevant (industrial) environment
TRL 4	Technology validated in lab
TRL 3	Experimental proof of concept
TRL 2	Technology concept formulated
TRL 1	Basic principles observed

Source: TRL scale definition in Horizon Europe projects, https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

cordin.arpagaus@ost.ch

HTHP Technologies

Indicated TRL levels

- **23 market available (TRL 8-9)**
- **7 prototype and demonstration systems (TRL 6-7)**
- **3 lab/small-scale prototypes (TRL 4-5)**

HTHP supplier (High-Temperature Heat Pump)	Product	Max. heating capacity (MW)	Max. supply temp. (°C)	TRL (Technology Readiness Level) 1	2	3	4	5	6	7	8	9
Spilling	Steam Compressor	15	280									9
Enerin	HoegTemp	10	250						6			
Qpinch	Heat Transformer	2	230									9
Piller	VapoFan	70	212								8	9
Olvondo	HighLift	5	200									9
Turboden	LHP	30	200							7	8	9
ToCircle	TC-C920	5	188						6	7		
Kobelco MSRC160	MSRC160	0.8	175									9
Kobelco SGH165	SGH165	0.62	175									9
Heaten	HeatBooster	6	165							7	8	9
SPH	Thermbooster	5	165						6	7	8	
SRM	Compressor for water vapor	2	165					5				
Siemens Energy	Industrial Heat Pump	70	160									9
Enertime	HTHPs	10	160				4	5	6	7	8	
Weel & Sandvig	WS Turbo Steam	5	160				4	5	6	7	8	9
Rank	Rank® HP	2	160							7		
MAN	ETES CO_2 Heat Pump	50	150							7	8	
Epcon	MVR-HP	30	150									9
Ohmia Industry	SPHP	10	150							7	8	
ecop	Rotation Heat Pump K7	0.7	150						6	7		
Mayekawa FC Comp	FC-compressor	1	145					5				
GEA Refrigeration	CO_2 Heat Pump	1.2	130								8	
Mitsubishi Heavy Ind.	ETW-S	0.6	130									9
Hybrid Energy	HyPAC-S	5	120									9
Johnson Controls	Cascade Heat Pump System	5	120							7	8	
Fenagy	H1800-AW/WW	1.8	120					5	6			
Mayekawa HS Comp	HS-compressor	0.75	120							7		
Kobelco SGH120	SGH120	0.37	120									9
Mayekawa EcoSirocco	Eco Sirocco	0.1	120									9
Fuji Electric	Steam Generation Heat Pump	0.03	120									9
Emerson	Cascade Solution	0.03	120						6			
Skala Fabrikk	SkaleUP	0.3	115							7		
Mayekawa EcoCircuit	Eco Circuit 100	0.1	100								8	9

Other suppliers:
- Ago Calora (150 °C)
- Ochsner (130 °C)
- Oilon (120 °C)
- PureThermal (120 °C)
- ThermoDraft (120 °C)
- Combitherm (120 °C)
- …

Large-scale:
- Friotherm
- MAN Energy Solutions
- Turboden
- Mitsubishi MHPS
- Siemens Energy
- …

Data source: IEA HPT Annex 58
https://heatpumpingtechnologies.org/annex58/task1

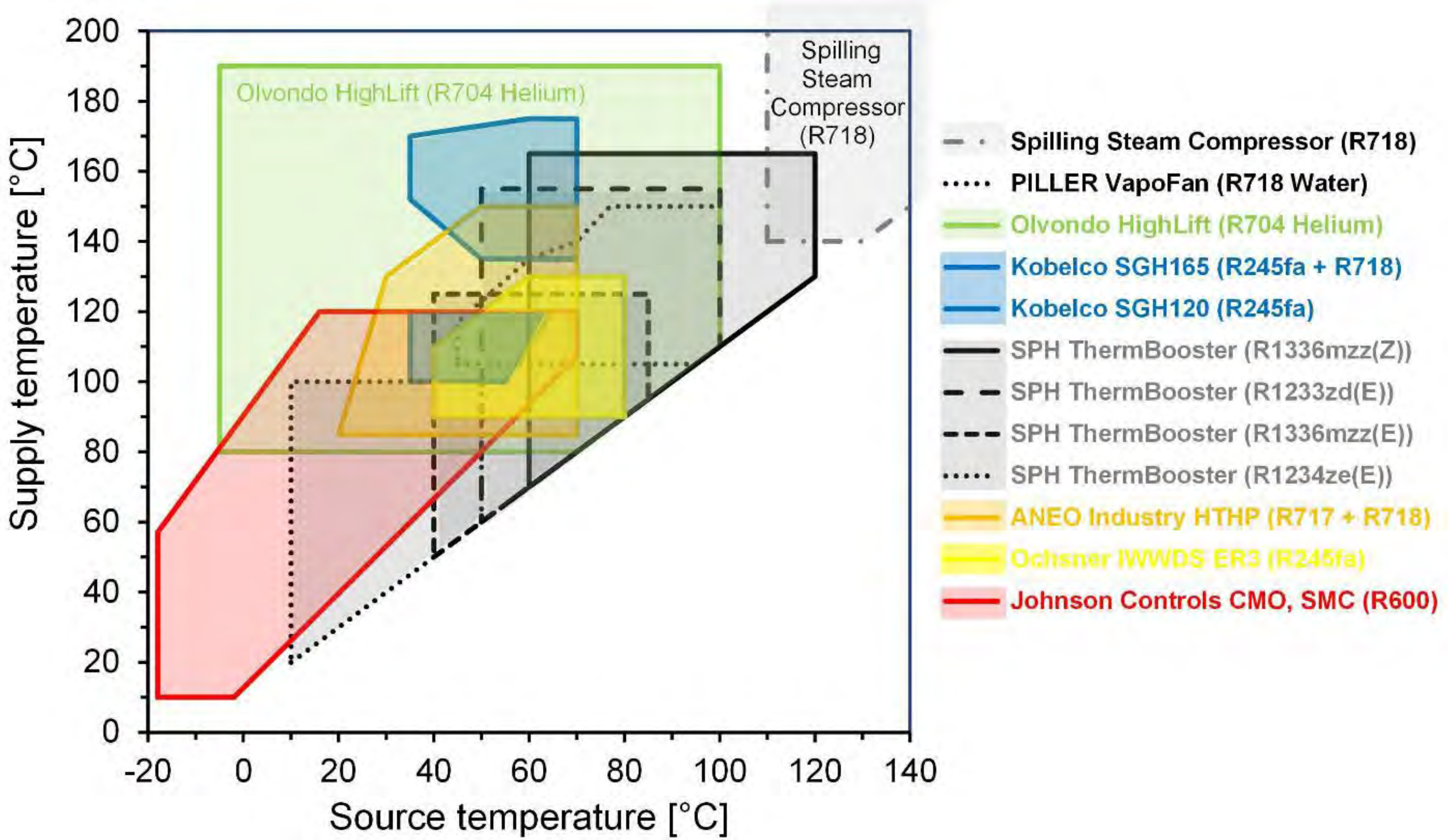
Note:

All information has been provided by the suppliers without third-party validation.

The information was provided as an indicative basis and may be different in final installations depending on application-specific parameters.

cordin.arpagaus@ost.ch

Operating maps of some industrial SGHPs

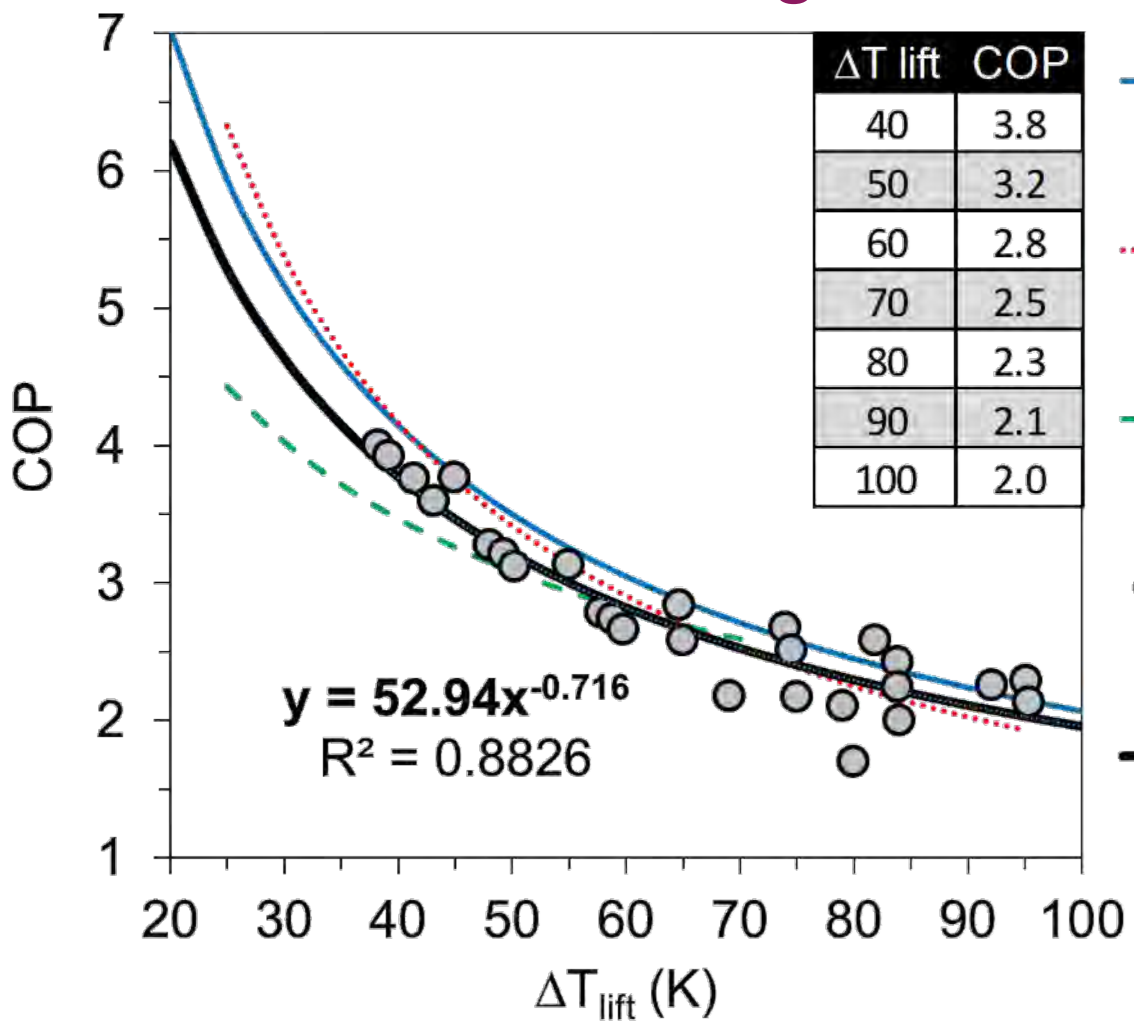


Source: Arpagaus et al. (2023): Integration of High-Temperature Heat Pumps in Swiss Industrial Processes (HTHP-CH), 14th IEA Heat Pump Conference, 15-18 May 2023, Chicago, USA

cordin.arpagaus@ost.ch

STEAM

COP of Steam Generating Heat Pumps



ΔT lift	COP
40	3.8
50	3.2
60	2.8
70	2.5
80	2.3
90	2.1
100	2.0

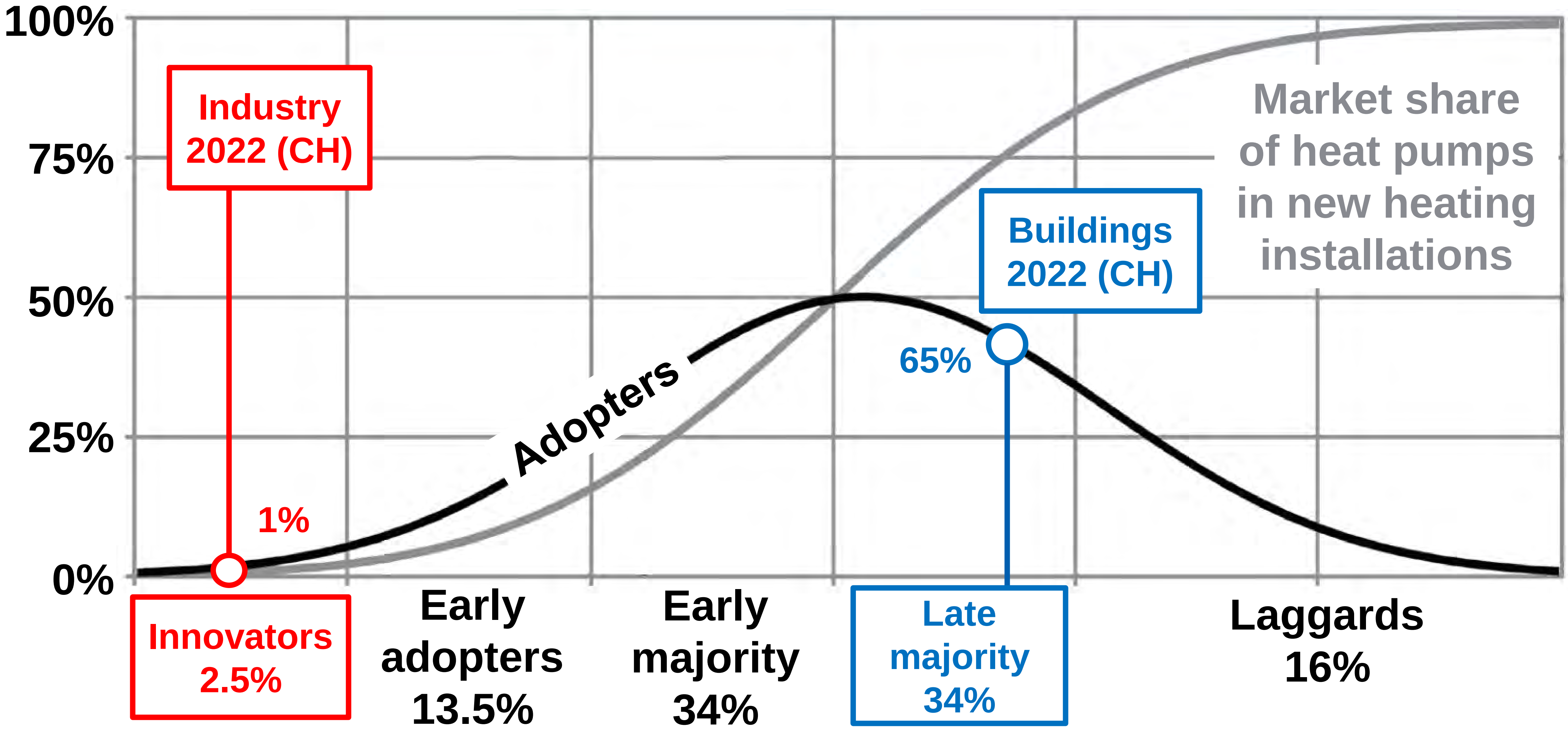
$$COP = 52.94 \cdot \Delta T_{lift}^{-0.716}$$

Source: Arpagaus, C., Bless, F., Bertsch, S.: Techno-economic analysis of steam generating heat pumps for integration into distillation processes, GL2022, 15th IIR-Gustav Lorentzen conference on Natural Refrigerants, 13-15 June 2022, Trondheim, Norway, http://dx.doi.org/10.18462/iir.gl2022.0029

cordin.arpagaus@ost.ch

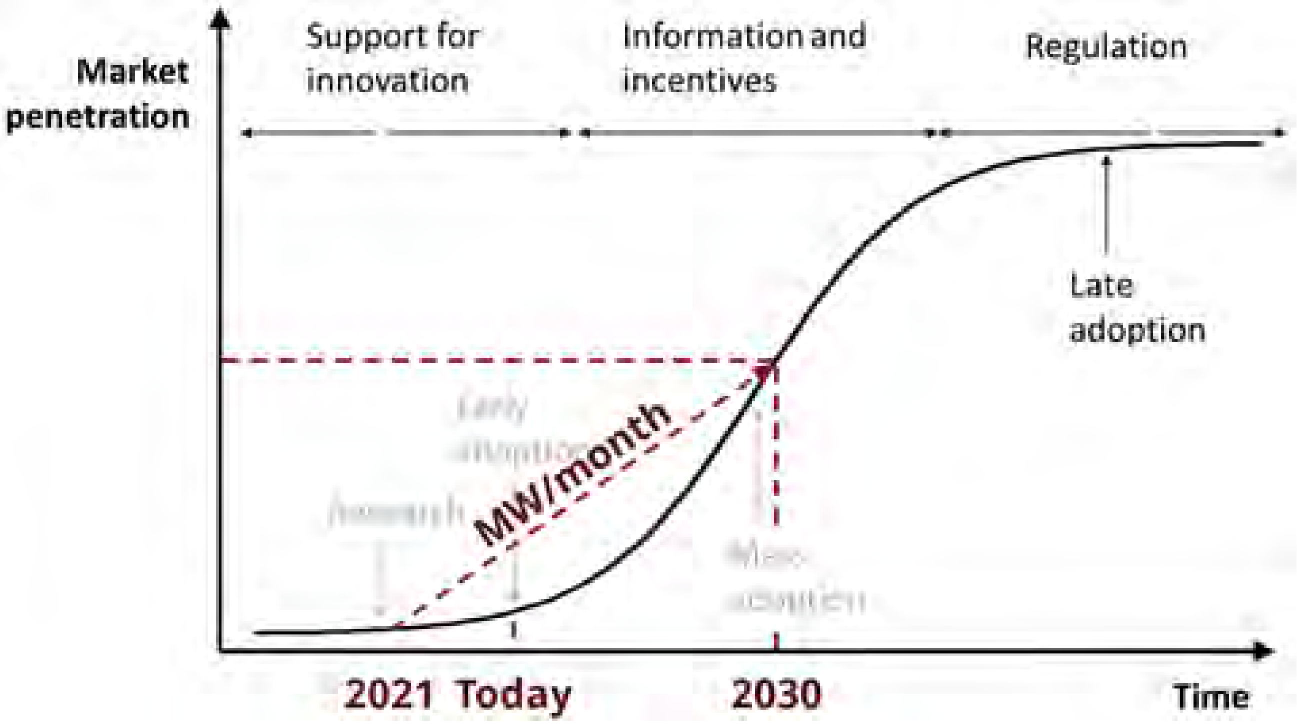
OST

Technology Adoption of Heat Pumps in Switzerland – Status 2022



cordin.arpagaus@ost.ch

S-curve of HTHP technology adoption



Source: Zühlsdorf (2024)

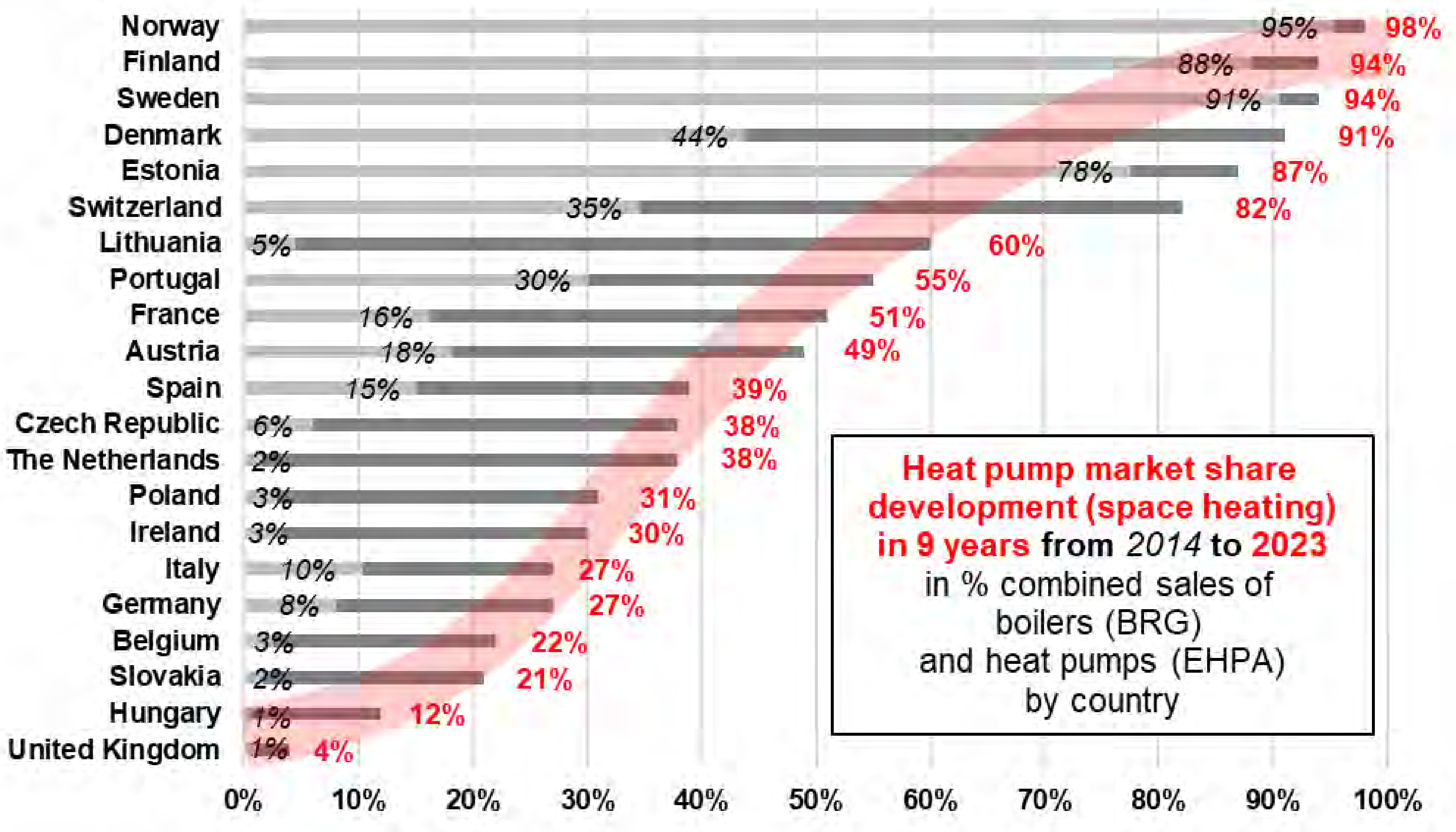
Favorable market conditions:

- Support for innovation and research
- More information
- Economic incentives
- Technology awareness
- Commitment to sustainability and decarbonization
- Involvement of various stakeholders

cordin.arpagaus@ost.ch

Market Adoption – S-curve by country for space heating

Heat pumps market share development over the last 9 years



Own illustration, Data source: EHPA Market Report Charts, https://stats.ehpa.org/home/report-charts

Sweden

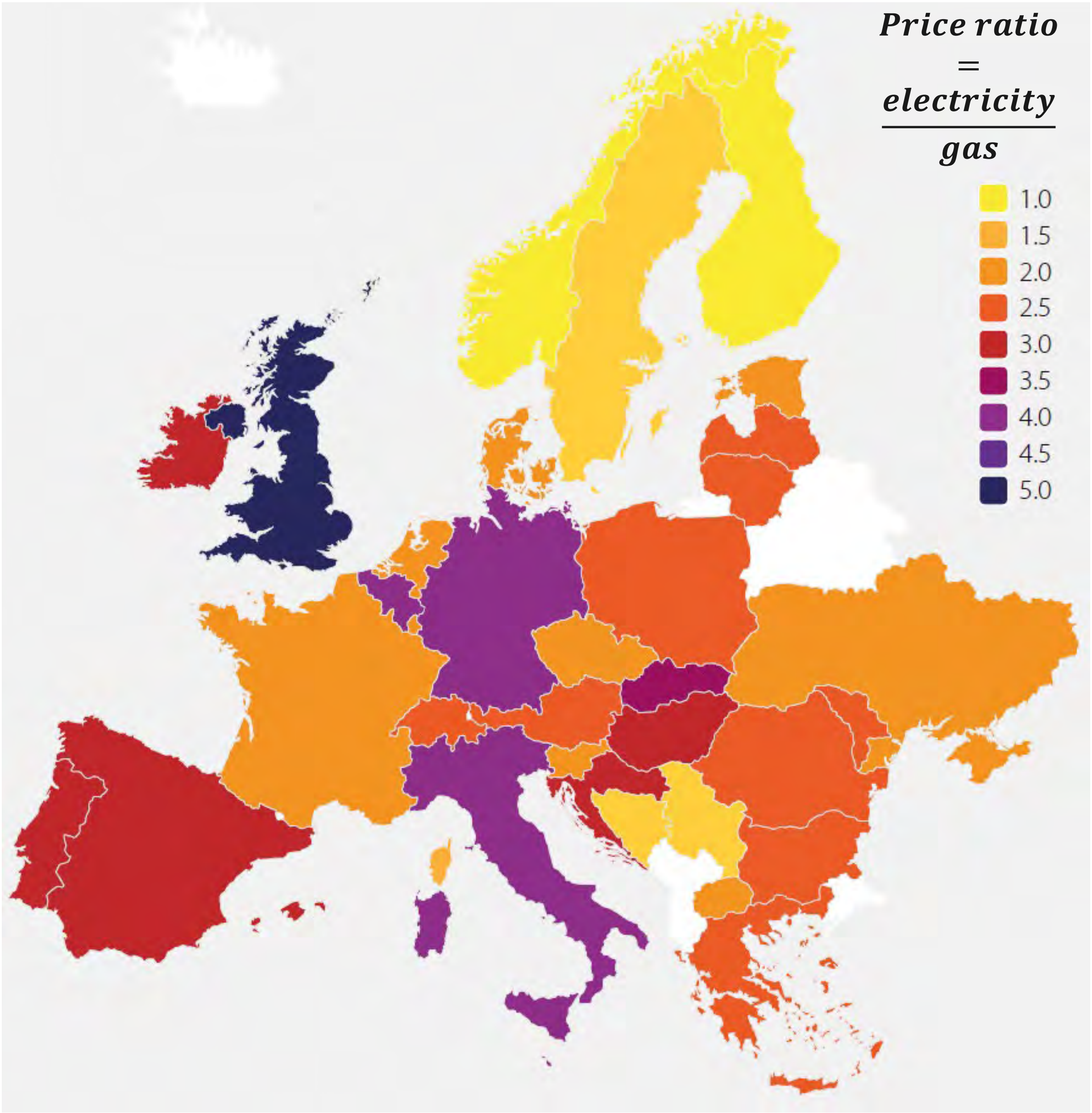
- Energy crisis end 1970s
- Shortage of oil
- Companies started developing heat pumps Hydro- and nuclear power
- Electricity is cheap and surplus
- Imports of oil unsecure

cordin.arpagaus@ost.ch

Market Attractiveness depends on Price Ratio between Electricity and Gas

- Decarbonization requires increased use of **renewable electricity**
- **Electricity is more expensive** than fossil fuel in many European countries

For small scale industrial
end-users with
2 GWh/a to 20 GWh/a electricity
3 GWh/a to 28 GWh/a gas



Source: De Boer et al. (2020): Strengthening Industrial Heat Pump Innovation, Decarbonizing Industrial Heat, White Paper, July 14, 2020

cordin.arpagaus@ost.ch

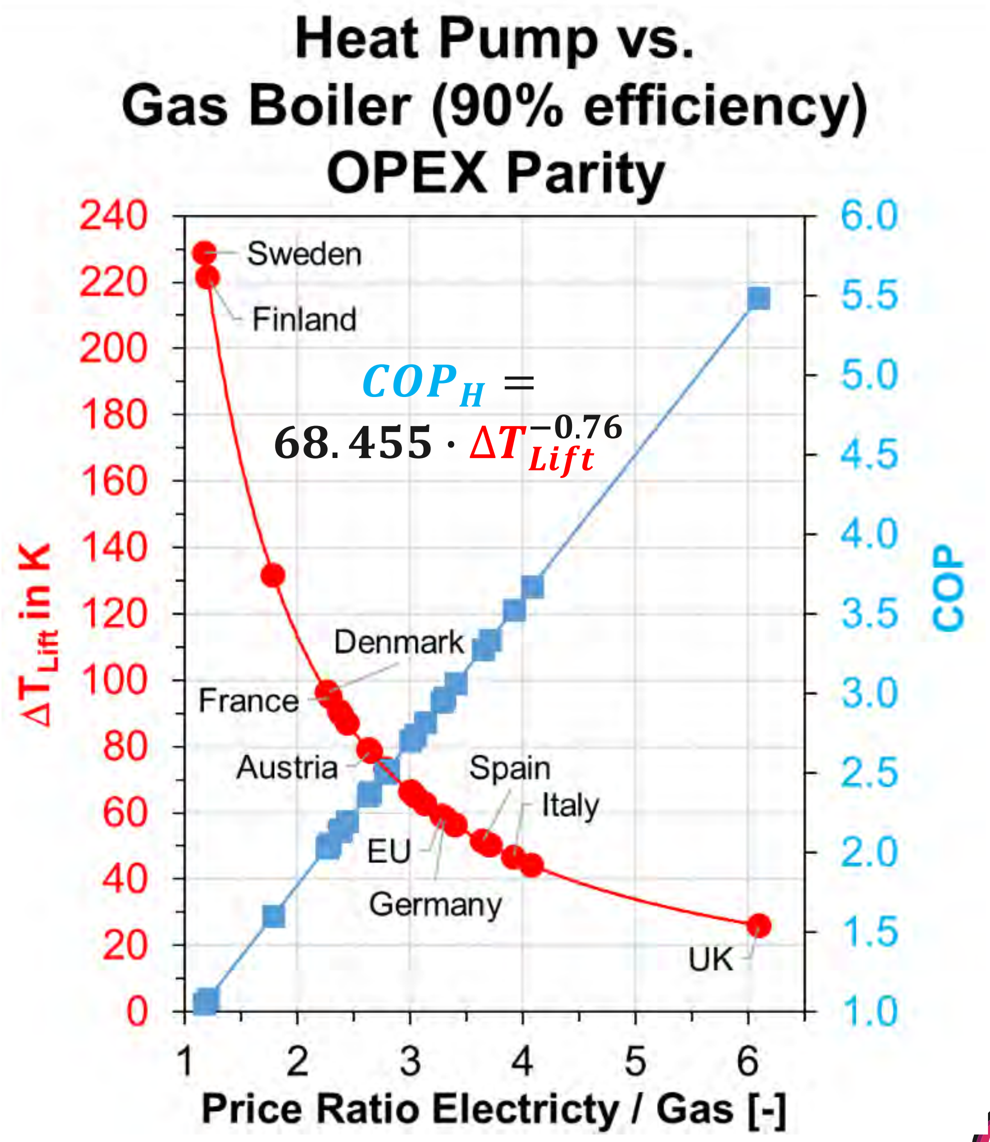
OPEX Parity COP and Temperature Lift

$$COP = \frac{Price_{Electricity}}{Price_{Gas}} \cdot \eta_{Gas\ Boiler}$$

90%

Country	Gas	Electricity	Price Ratio	COP	ΔT_Lift
	Prices without refundable			OPEX Parity	
Sweden	**4.1**	**4.8**	**1.17**	**1.1**	**229**
Finland	**4.5**	**5.4**	**1.20**	**1.1**	**222**
Luxembourg	2.3	4.1	1.78	1.6	132
Lithuania	3.0	6.8	2.27	2.0	96
Denmark	**3.1**	**7.0**	**2.26**	**2.0**	**96**
France	**2.8**	**6.4**	**2.29**	**2.1**	**95**
Netherlands	2.6	6.2	2.38	2.1	90
Slovenia	2.5	6.1	2.44	2.2	87
Estonia	3.0	7.1	2.37	2.1	91
Czech Republic	2.4	6.3	2.63	2.4	79
Austria	**2.8**	**7.4**	**2.64**	**2.4**	**78**
Latvia	2.7	7.5	2.78	2.5	73
Hungary	2.5	7.0	2.80	2.5	73
Greece	2.5	7.5	3.00	2.7	66
Poland	2.4	7.2	3.00	2.7	66
Romania	2.3	7.0	3.04	2.7	65
Croatia	2.3	7.2	3.13	2.8	63
Belgium	2.0	6.8	3.40	3.1	56
Germany	**2.6**	**8.6**	**3.31**	**3.0**	**58**
Bulgaria	2.0	6.8	3.40	3.1	56
Spain	**2.5**	**9.1**	**3.64**	**3.3**	**51**
Portugal	2.4	8.9	3.71	3.3	50
Ireland	2.7	10.0	3.70	3.3	50
Italy	**2.4**	**9.4**	**3.92**	**3.5**	**47**
Slovakia	2.5	10.2	4.08	3.7	44
UK	**2.1**	**12.8**	**6.10**	**5.5**	**26**
EU	**2.5**	**8.2**	**3.28**	**3.0**	**59**

Market Attractiveness



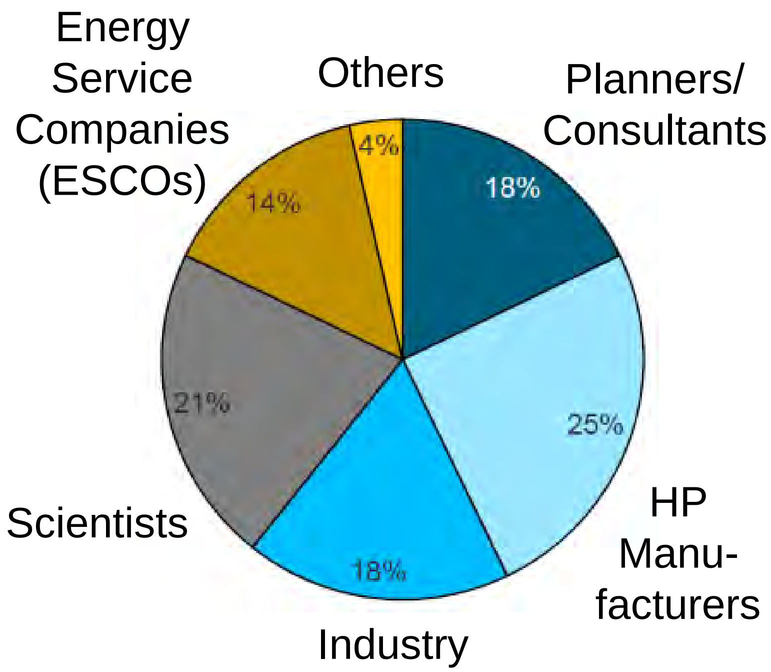
cordin.arpagaus@ost.ch

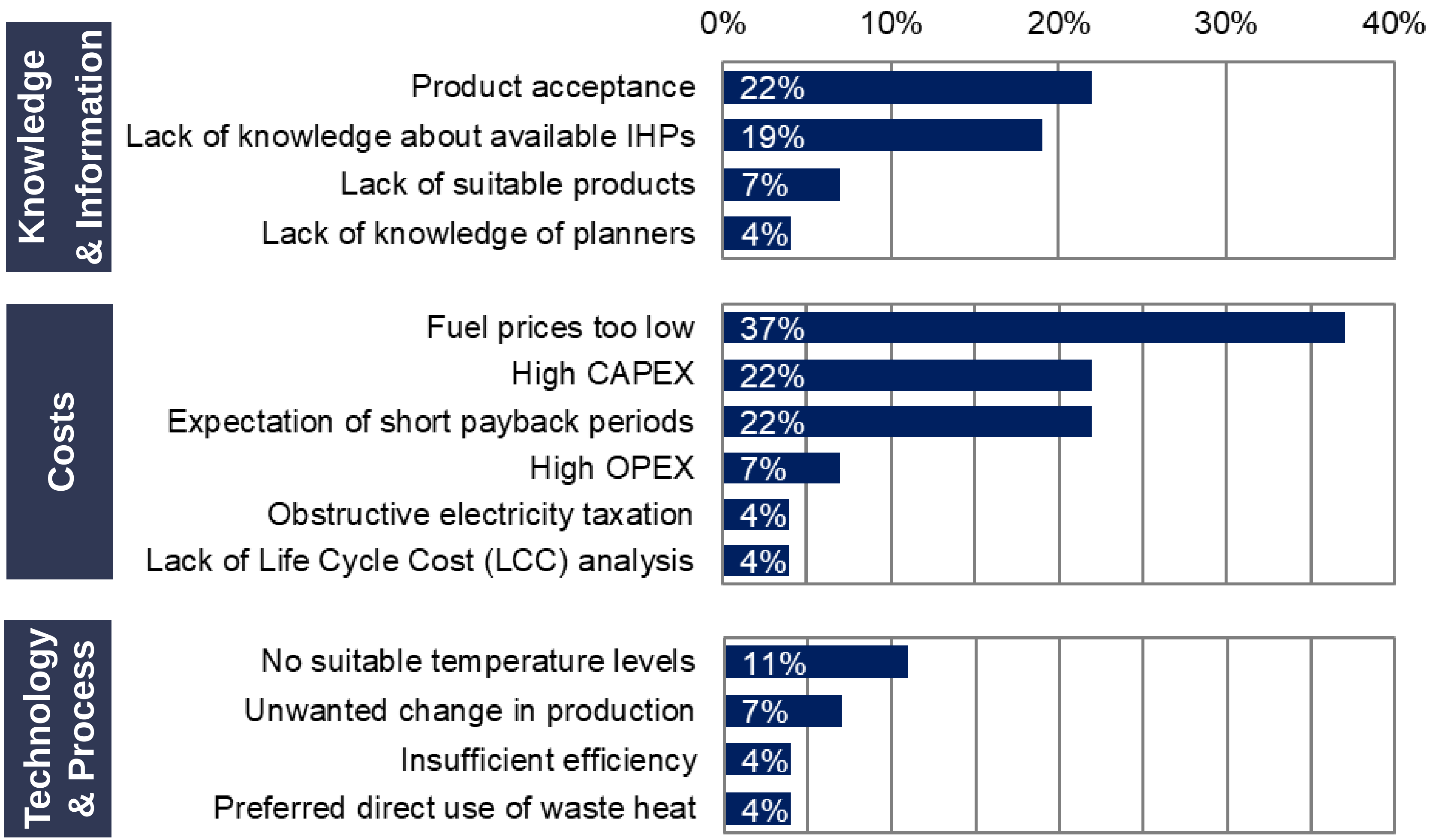
OST

Market Analysis – Potential of Steam-Generating Heat Pumps

Challenging economics identified as key market barrier

Survey among 27 experts on heat pumps and heat recovery



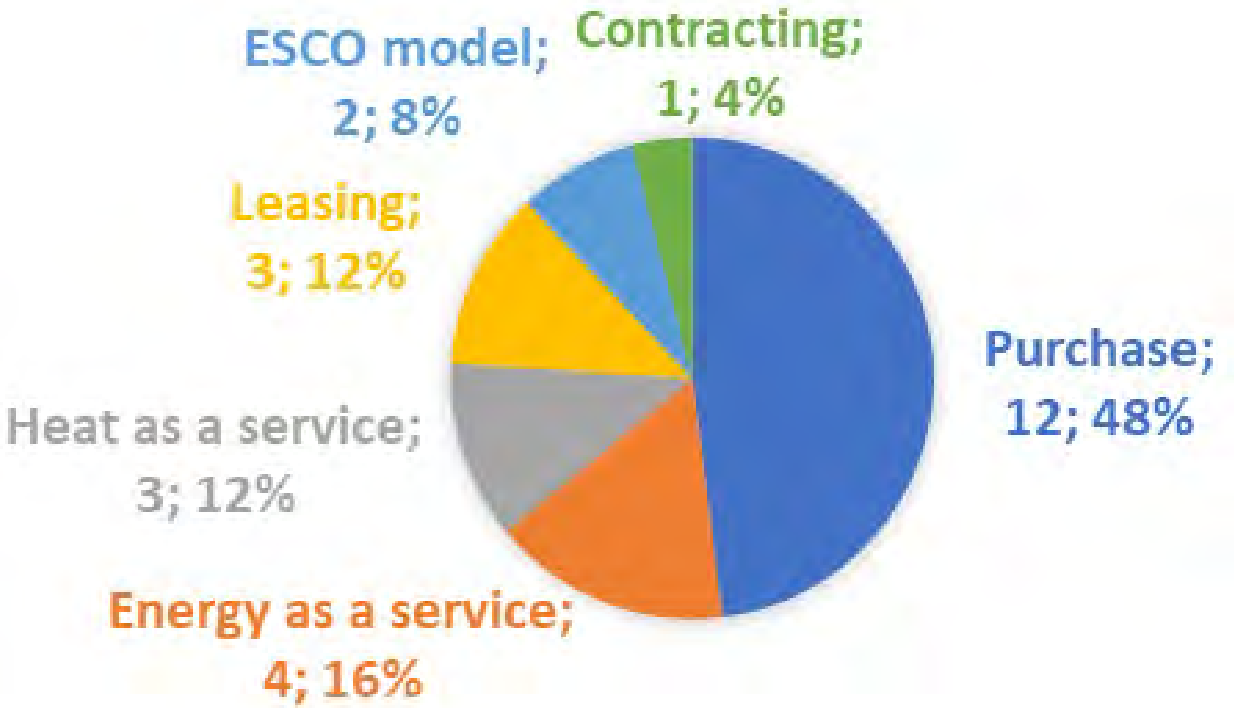


Source: Data adapted from Wolf et al. (2017): Systematische Anwendung von Großwärmepumpen in der Schweizer Industrie, Endbericht, 10. Mai 2017 and Wolf (2020): Rahmenbedingungen und Märkte für Industriewärmepumpen, ETV Online Tagung 2020, Industrielle Gross- und Hochtemperaturwärmepumpen im Energiesystem, 22. Juli 2020

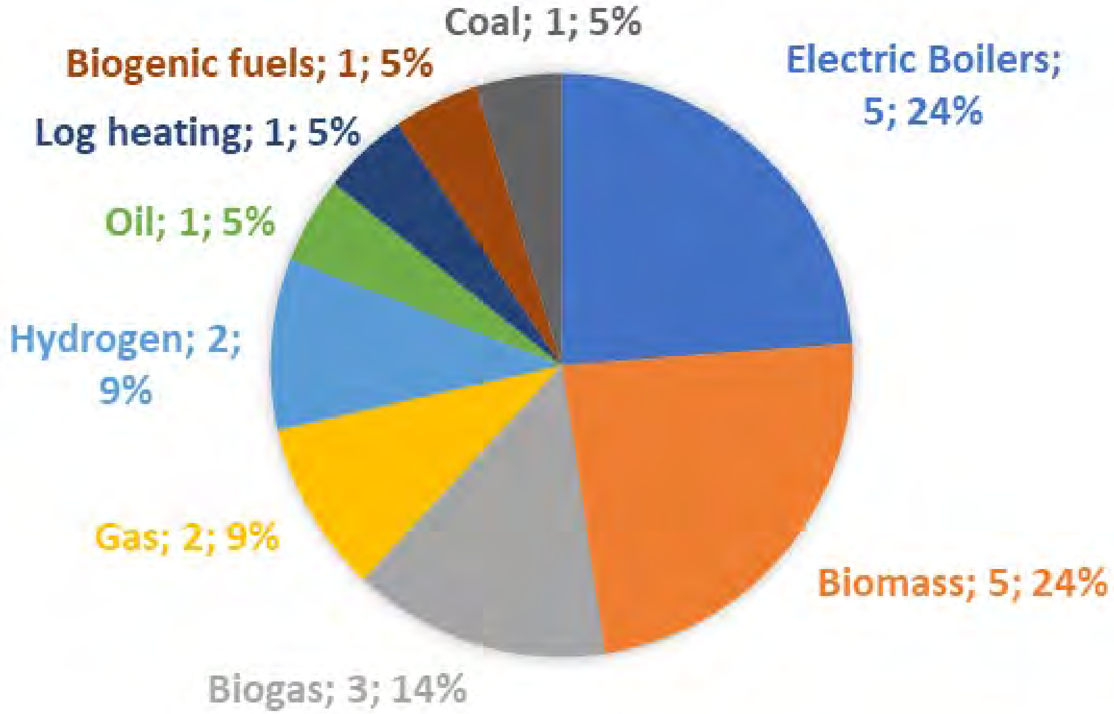
cordin.arpagaus@ost.ch

Interview results with 16 HTHP manufacturers (in Q4/2023)

Promising Business Models



Possible Substituting Technologies



- **Direct2Customer (purchase) appears to be the most widespread business model** (i.e., direct sales, installation commissioning, maintenance, ownership)
- **New market opportunities** are especially **Heat-as-a-Service (HaaS)** (highly customer-integrated)
- **Alternative heating solutions** (i.e., electric boilers, biomass, biogas,

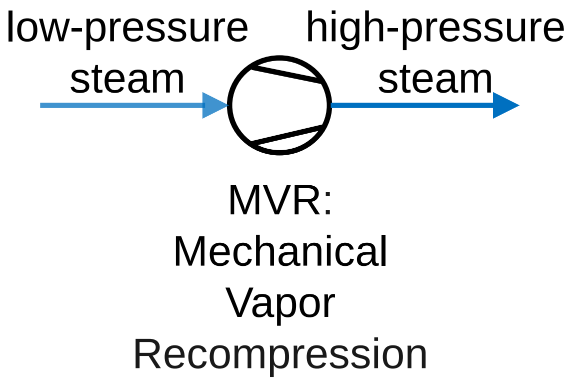
Source: Arpagaus et al. (2024): Business models for high-temperature heat pumps, HTHP Symposium 2024, 23-24 January 2024, Copenhagen, Denmark

cordin.arpagaus@ost.ch

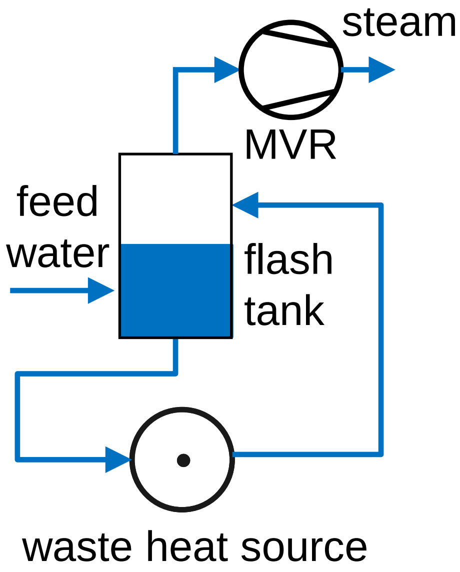
STEAM

Heat pump cycles

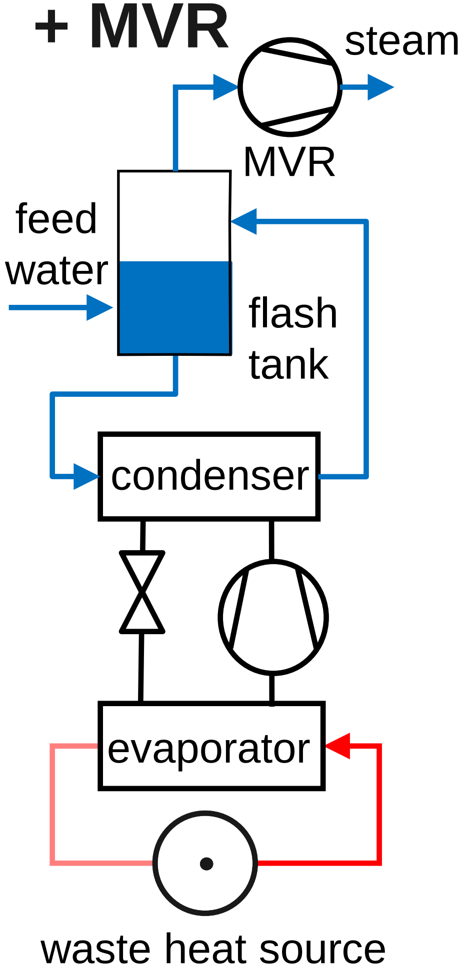
MVR



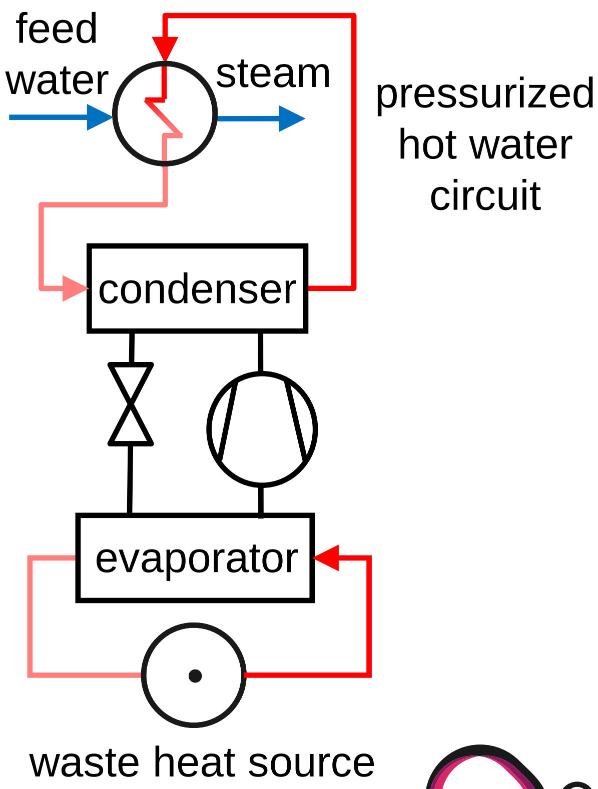
Flash tank + MVR



Closed cycle + flash tank + MVR



Closed cycle + pressurized hot water + steam generator



Source: [Arpagaus (2024): IEA HPT Annex 58 HTHP Final Webinar, 23 April 2024]

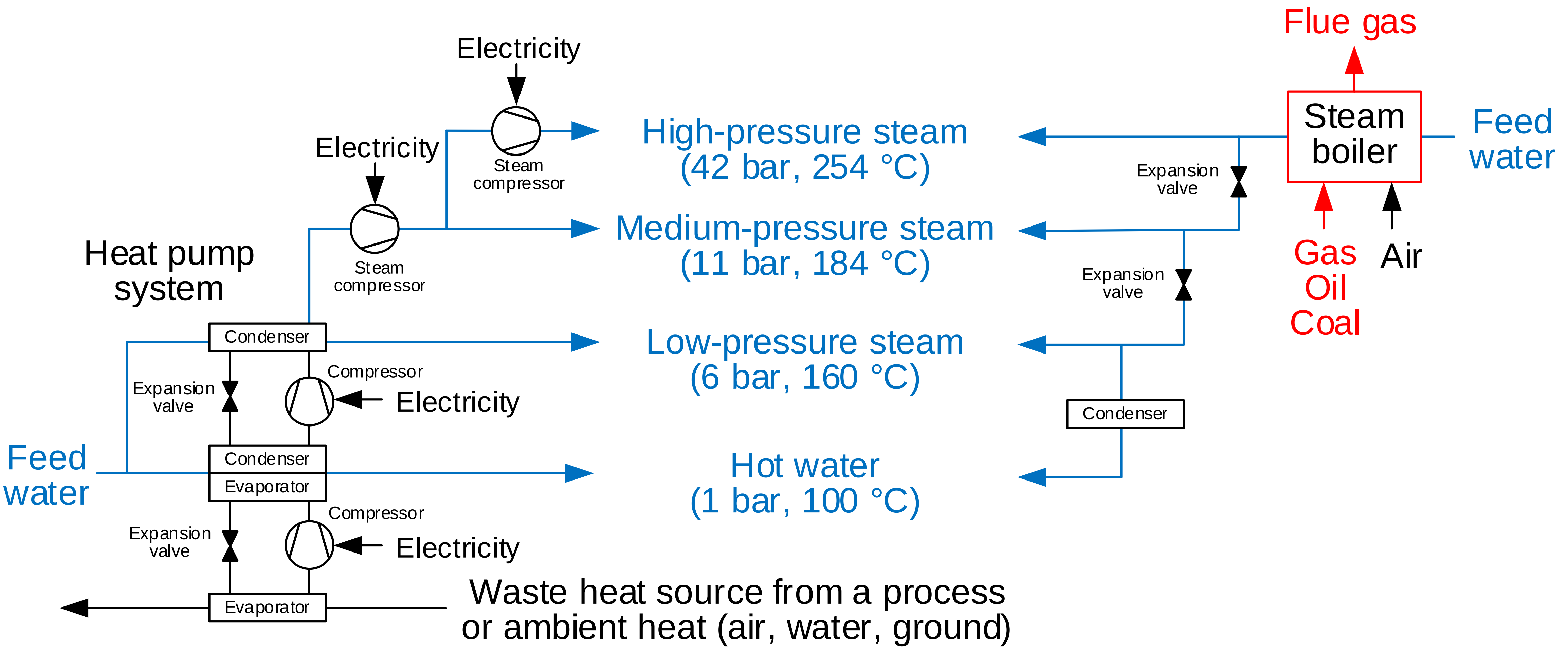
cordin.arpagaus@ost.ch

OST

Steam supply with a heat pump system

STEAM

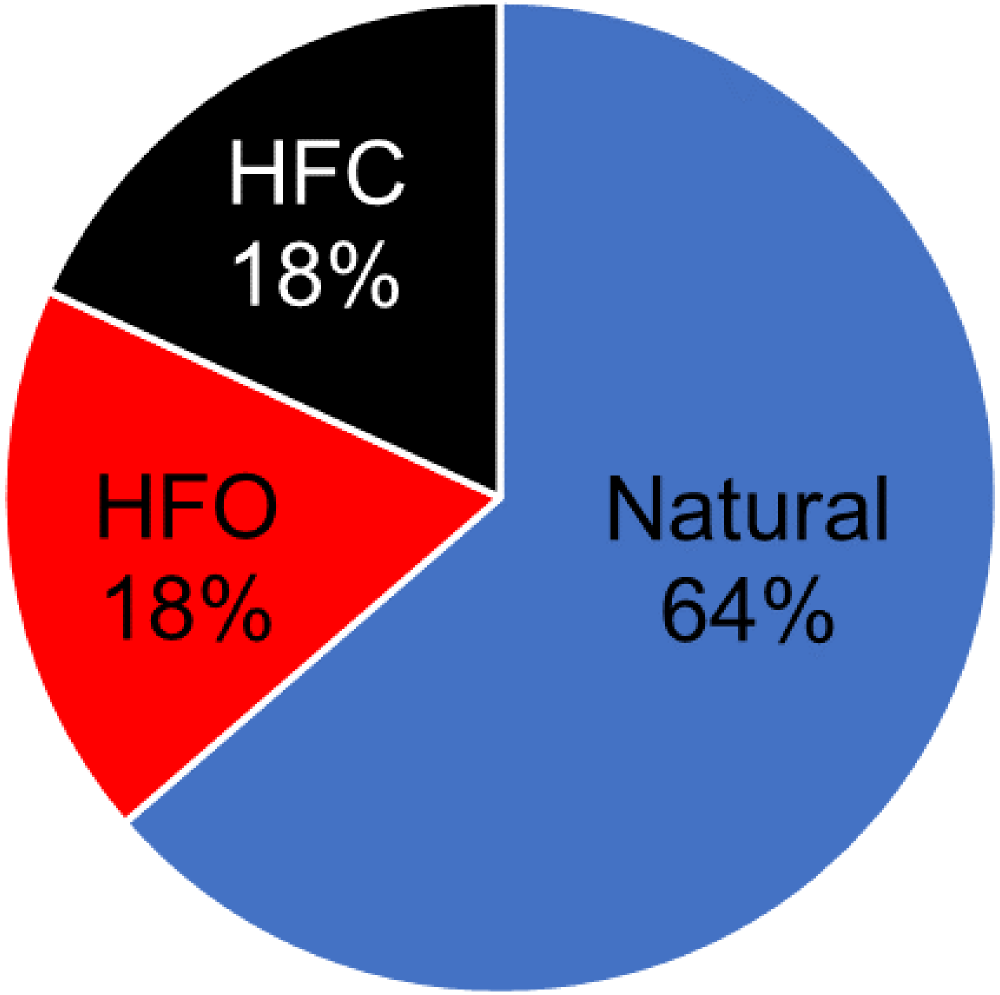
- Heat pump steam generators are efficient technology for industrial waste heat recovery



Source: Adapted from IEA HPT Annex 58 High-Temperature Heat Pumps, Task 2 Report Integration Concepts, April 2024

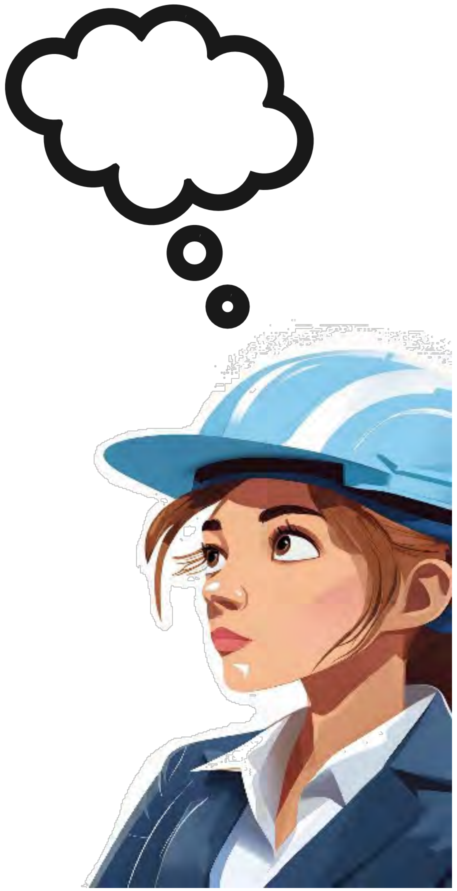
cordin.arpagaus@ost.ch

Refrigerants in HTHPs



R718 (Water)	12
R744 (CO2)	4
R717 (Ammonia)	4
R601 (n-Pentane)	1
R600 (n-Butane)	3
R290 (Propane)	1
R704 (Helium)	2
ecop (Nobel gas)	1
R1336mzz(Z)	2
R1233zd(E)	3
R1234ze(E)	1
HFOs	2
R245fa	5
R410a	1
R134a	2

Natural	28
HFO	8
HFC	8



Based on data from IEA HPT Annex 58
https://heatpumpingtechnologies.org/annex58/task1

cordin.arpagaus@ost.ch

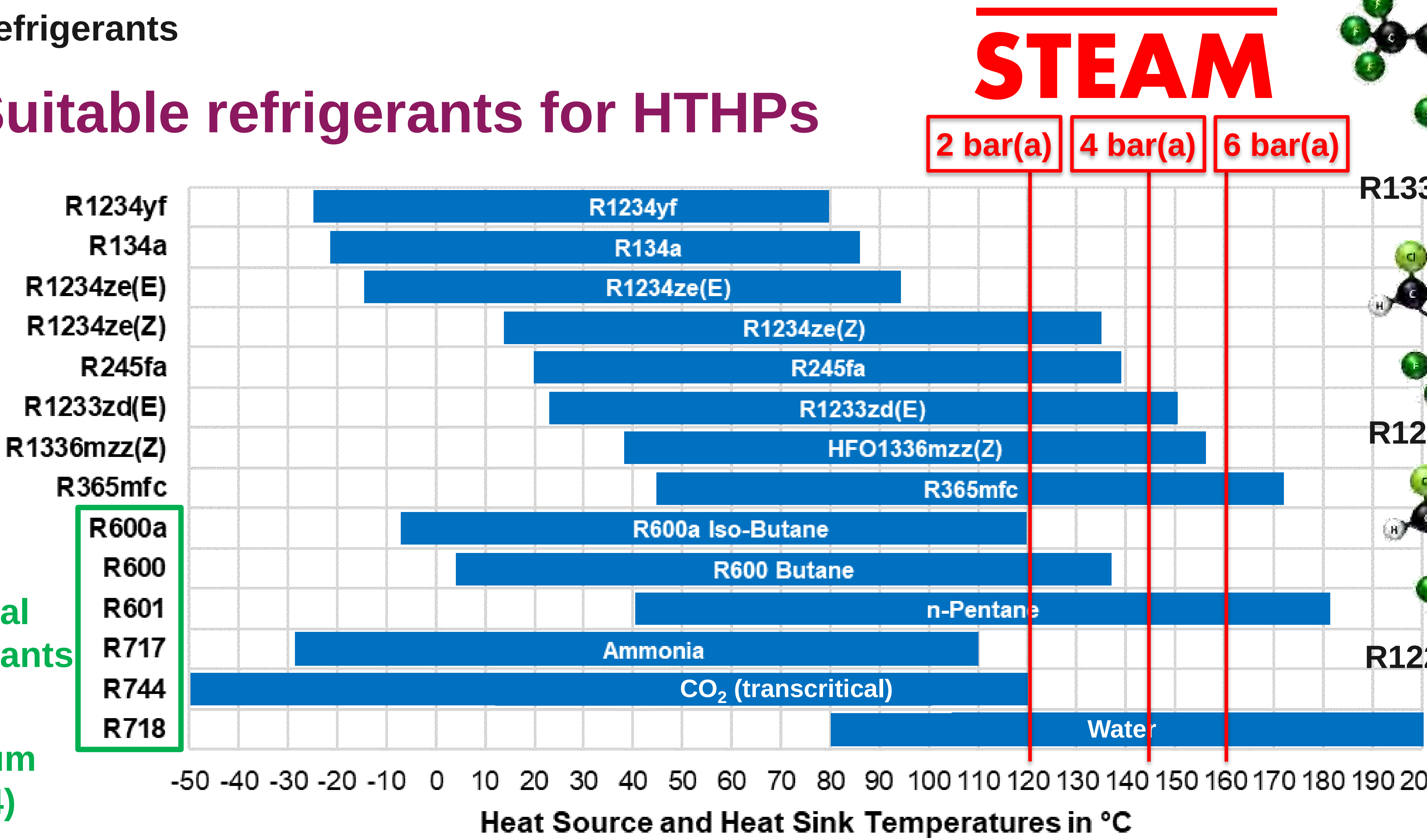
Refrigerants

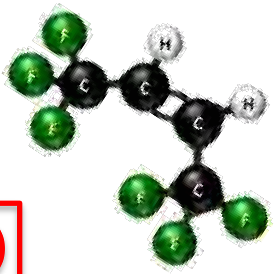
Suitable refrigerants for HTHPs

HFO
HFC
HFO
HFO
HFC
HCFO
HFO
HFC

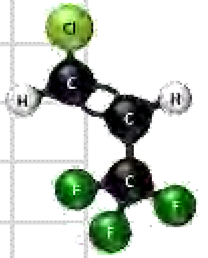
Natural Refrigerants

+ Helium (R704)





R1336mzz(Z)



R1233zd(E)

R1224yd(Z)

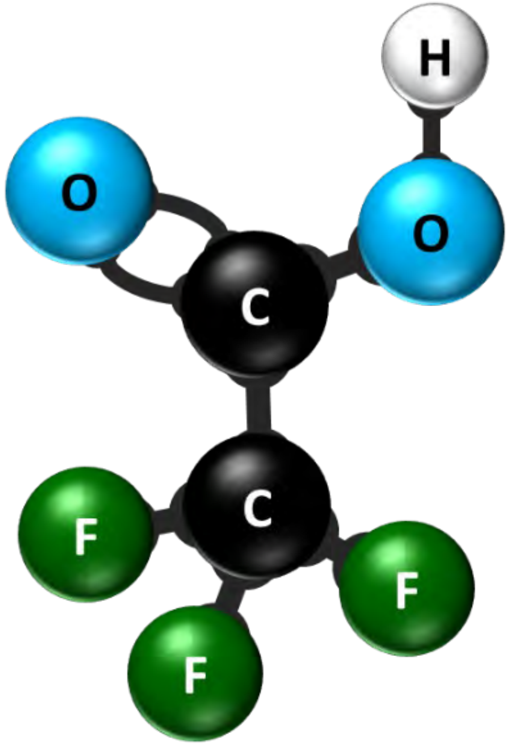
cordin.arpagaus@ost.ch

OST

Formation of trifluoroacetic acid (TFA, CF_3COOH)

Trifluoroacetic acid (TFA)

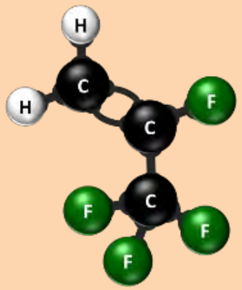
CF_3-C(O)OH



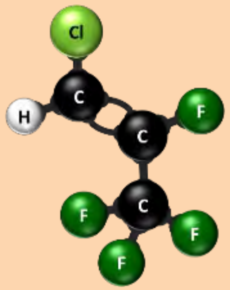
- TFA is an end product of atmospheric degradation of halogenated refrigerants
- Persistent in the environment and also mobile in the aquatic environment
- TFA can basically be formed from various substances, the presence of a **CF_3-CF= group** is considered a prerequisite for TFA formation

cordin.arpagaus@ost.ch

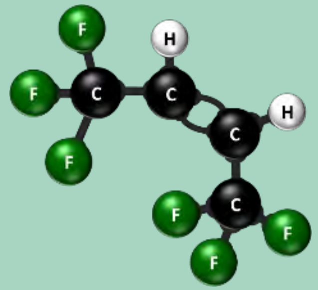
Molar yield of TFA during atmospheric degradation of HFOs



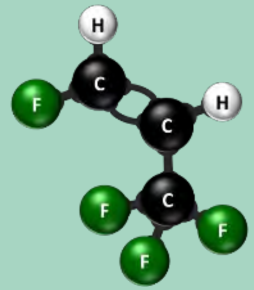
R1234yf
CF_3-CF=CH_2



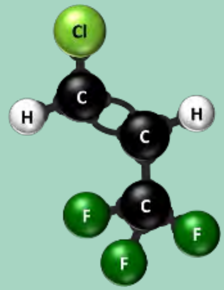
R1224yd(Z) [1)]
Z-**CF_3-CF**=CHCl



R1336mzz(Z) [2)]
Z-**CF_3-CH**=$CHCF_3$

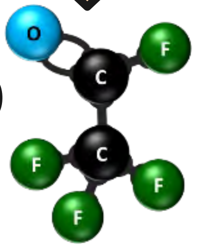


R1234ze(Z)
Z-**CF_3-CH**=CHF



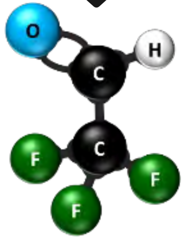
R1233zd(E) [3)]
E-**CF_3-CH**=CHCl

CF_3-CF=
group



Trifluoracetyl fluoride (TFF)
CF_3-C(O)F

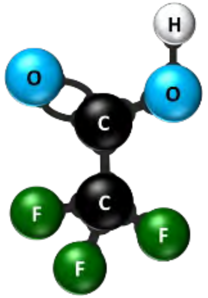
CF_3-CH=
group



Trifluoracetaldehyde
CF_3-C(O)H

[1)] 97%
(Guo et al., 2019)

~ 100%



Trifluoroacetic acid (TFA)
CF_3-C(O)OH

< 10%

[2)] < 20%, because of 2 x CF_3-CH=
(Henne et al., 2012)
[3)] ~2% (Sulbaek Andersen et al., 2018)

cordin.arpagaus@ost.ch

OST

How does a test laboratory for HTHPs looks like?

Laboratory for testing the ThermBooster™

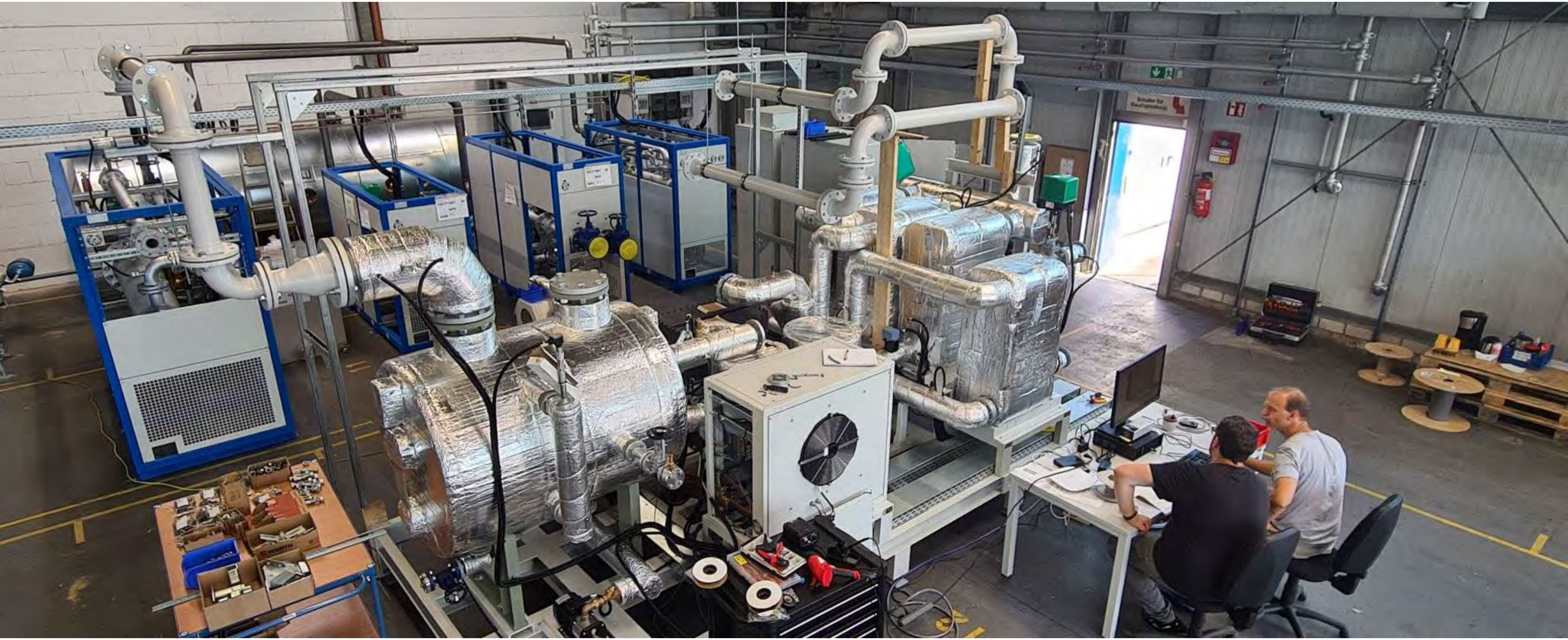


Image courtesy by SPH Sustainable Process Heat GmbH

cordin.arpagaus@ost.ch

www.push2heat.eu

Steam Generating Heat Pump

Industry sector	Demo 1: Paper industry
Plant owner	Felix Schoeller Group
Location	Weissenborn, Germany
Heat pump supplier	SPH
Heat pump technology	**2-stage cascade with 2 piston and 2 screw compressors**
Refrigerants (1st stage, 2nd stage)	2 x 180 kg R515B, 350 kg R1233zd(E)
Size (L x W x H)	11 x 3 x 3 m (in container)
Heat source inlet / outlet (waste heat)	**46 °C / 41 °C** (exhaust humid air from paper machine dryer using a water-glycol circuit)
Heat sink inlet / outlet	**90 °C / 123.5 °C** low-pressure steam at 2.2 bar(a)
Heating capacity	**1’180 kW**
Steam mass flow rate	1’800 kg/h
Cooling capacity	690 kW
Electrical power	517 kW
COP (Carnot efficiency)	**2.3 (43%)**

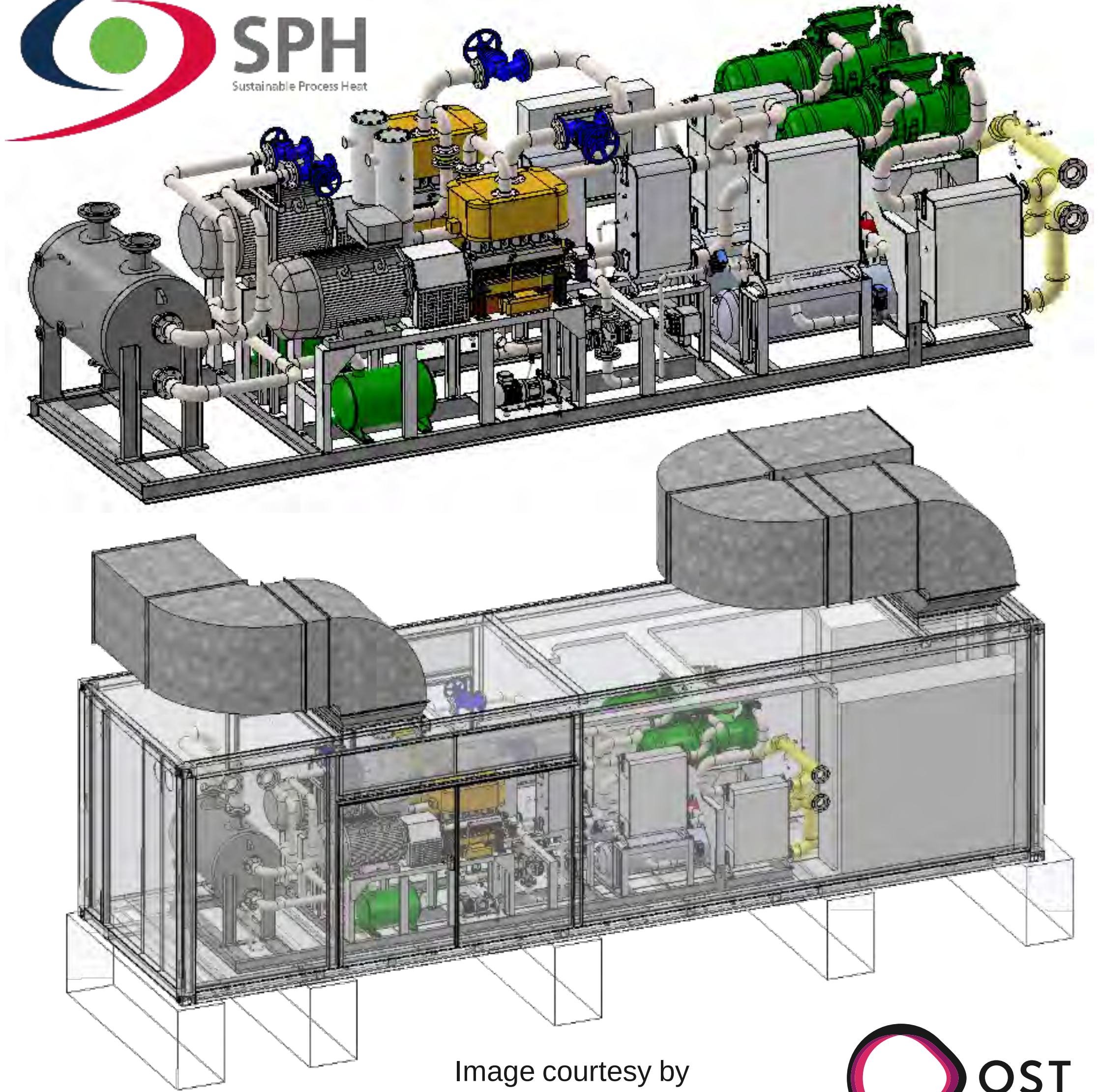


Image courtesy by
SPH Sustainable Process Heat GmbH

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

cordin.arpagaus@ost.ch

Steam generator and condenser from VAHTERUS

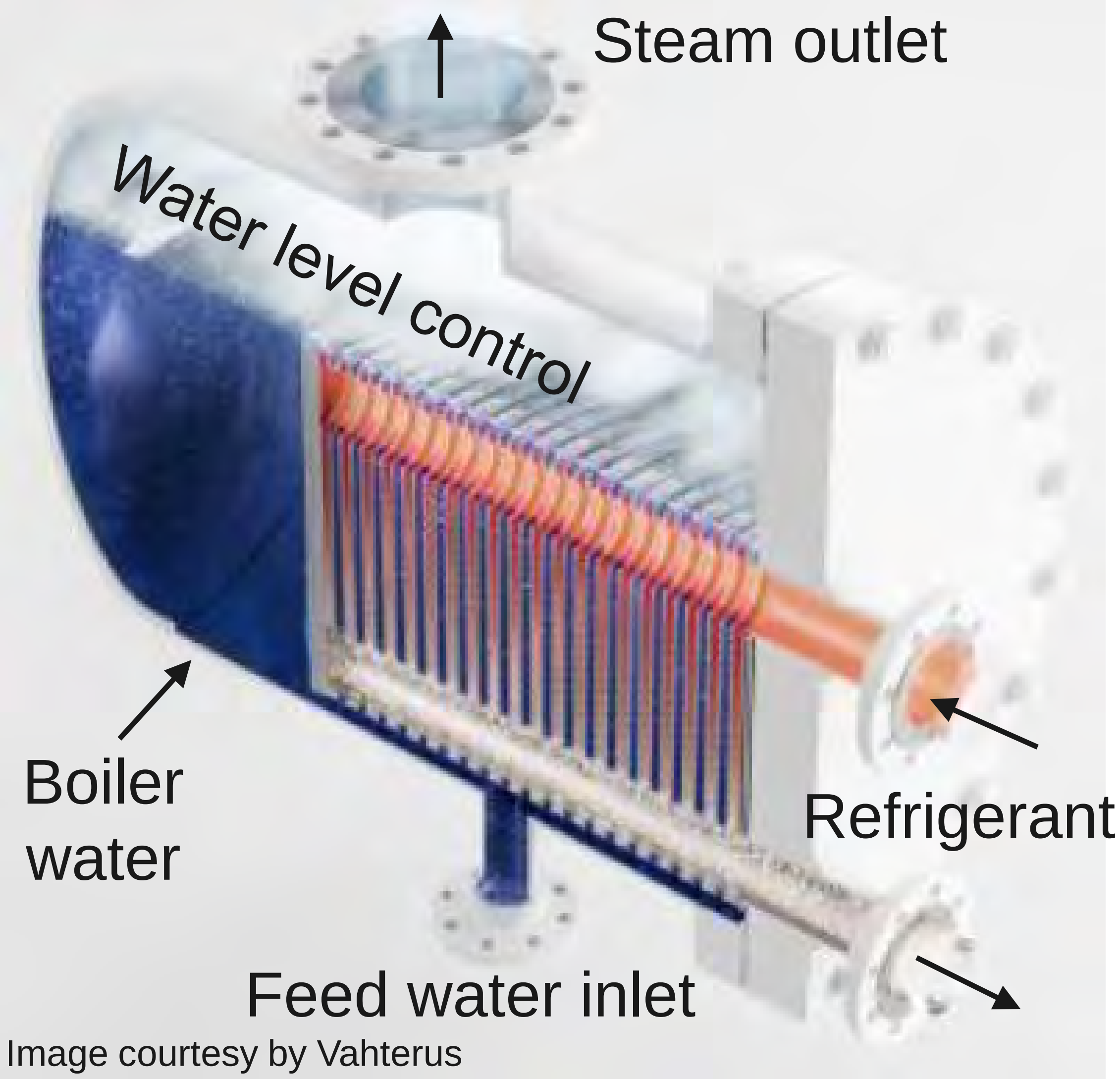


Image courtesy by Vahterus

- **Plate & Shell Heat Exchanger (PSHE)** with additional water volume for more stable steam production
- **Direct production of saturated steam** in the condenser of the heat pump
- **Highest efficiency** (lowest pinch point between refrigerant condensation and steam evaporation)
- **Shell as steam boiler** (fully welded)
- **Robust circular plates as condensers for the refrigerant** (e.g., R1233zd(E))
- Compact and light design
- Easy maintenance (no gaskets)

cordin.arpagaus@ost.ch

The first zero-emission distillery in Ireland

AHASCRAGH
DISTILLERY

Ahascragh Distillery
2.703 Follower:innen
1 Jahr • Bearbeitet •

Some major equipment arrivals over the past few days.

The last of our heat pump equipment is in place. This technology is a first for the industry. Furthermore, these heat pumps are the first in Ireland to reach up to 120 degrees.

Source: LinkedIn post

- Combined process cooling and process heating
- Design supply temperature: 115 °C
- Heating capacity: 1 MW
- Splitting heating demand into several temperature levels increases the system’s efficiency

oilon

2 x P450 series heat pumps (can generate 120 °C)
1 x P150 series heat pump

cordin.arpagaus@ost.ch

HTHPs for Pet Food Dryers

First electric counterflow dryer from Geelen Counterflow with 15 drying decks for drying aqua feed at the Cargill-Ewos plant in Bergneset, Norway

Source: YouTube Video

Images by courtesy of Geelen Counterflow

4 x HTHPs from Combitherm (3.5 MW heating capacity, R1233zd(E), screw compressor from Bitzer) use the dryer exhaust air as a heat source and generate 120 °C via an intermediate circuit to heat the drying air

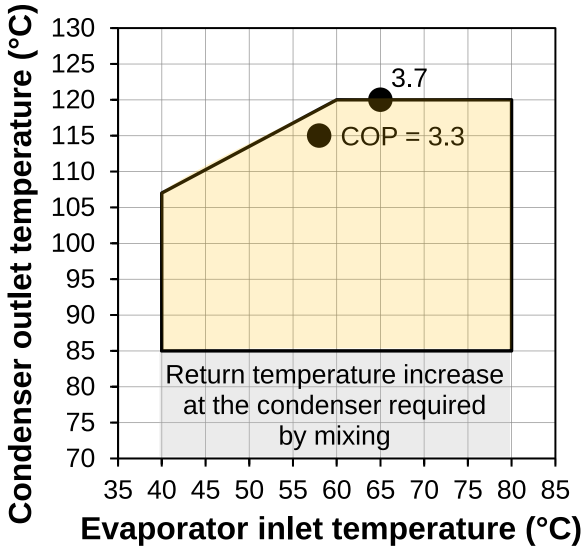
Source: YouTube Webinar

cordin.arpagaus@ost.ch

HTHP for direct steam generation

OCHSNER ENERGIE TECHNIK

Operating map and performance



- 1-stage cycle with economizer
- 2 semi-hermetic screw compressors in parallel
- Shell and tube evaporator

- Heating capacity max. 1’640 kW
- Refrigerant R1233zd
- Weight 15 tons
- Footprint 5.2 m^2

- **Application: Steam for paper drying**
- Currently laboratory demonstration (TRL 4)

Source: IEA HPT Annex 58 HTHP Factsheet OCHSNER Energie Technik (May 2024)

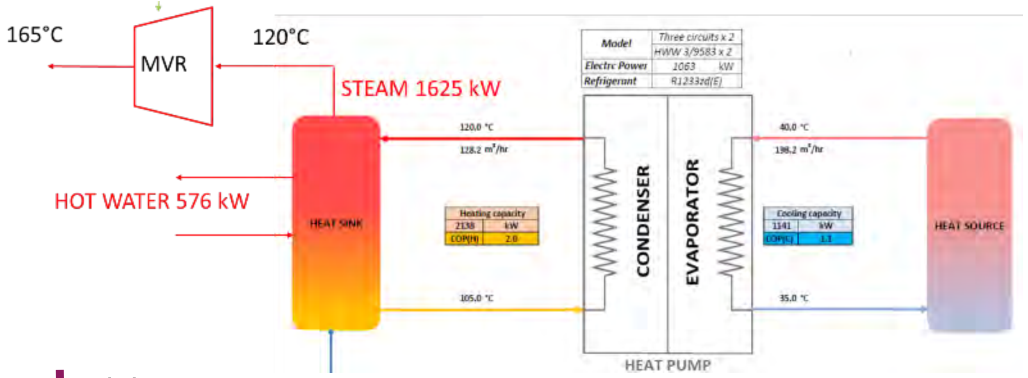
cordin.arpagaus@ost.ch

HTHP with Steam Evaporator


Images courtesy by COMBITHERM GmbH


HTHP with flash tank


Technical training of Armstrong team at COMBITHERM GmbH in Fellbach, Germany



- HTHP demo unit with **R1233zd(E)** refrigerant producing **pressurized hot water up to 120 °C and flash steam**
- The **largest HTHP unit (HWW 3/9583 x 2) with 3 screw compressors** can generate **more than 1 t/h of steam**
- If higher temperatures are required, a **steam compressor can be applied to reach 200 °C**

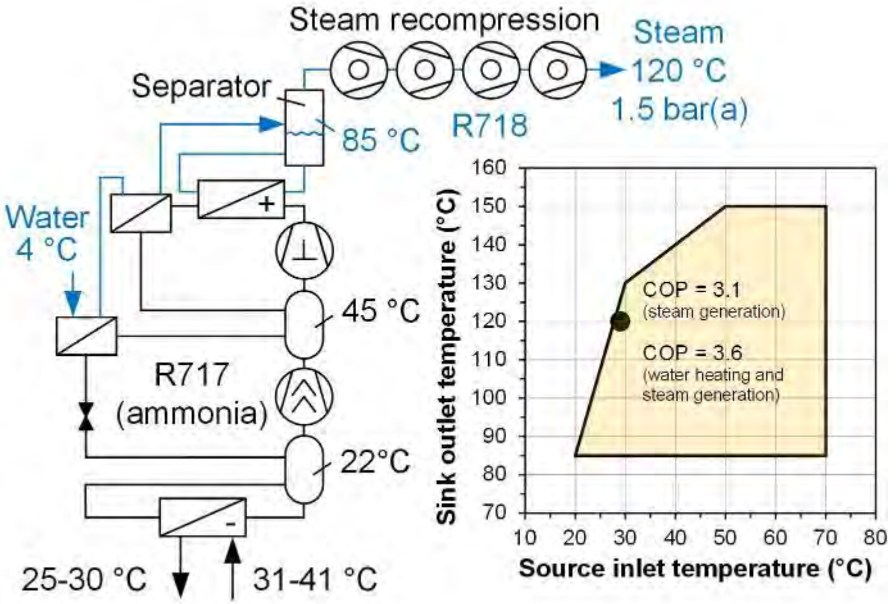
Source: LinkedIn Post (2024) by Rossen Ivanov, Armstrong and EHPA Webinar (2024)

cordin.arpagaus@ost.ch

OST

New Developments and Products

Steam producing heat pump



- **Closed-loop R717 (ammonia) bottom cycle with 1 screw and 1 piston compressor and open-loop R718 (water) top cycle with 4 centrifugal fans**
- **Application: Heat recycling for petfood pellets process, waste heat recovery of moist air**
- Heating capacity 1.6 MW, 2 t/h steam, 120 °C, 1.5 bar(a)
- TRL 8, footprint around 80 m^2 with auxiliaries, weight 30 tons

Source: Schlemminger and Bantle (2024): OST Webinar Presentation (18.3.2024) and IEA HPT Annex 58 HTHP Factsheet ANEO Industry AS (8/2023)

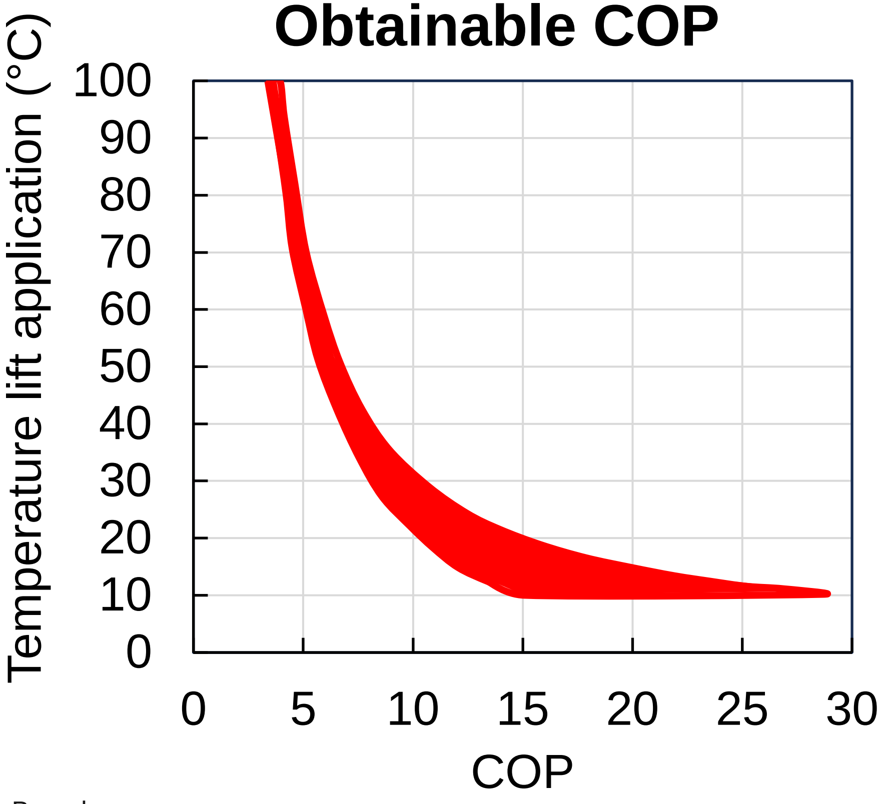
cordin.arpagaus@ost.ch

Products for Mechanical Vapor Recompression (MVR)

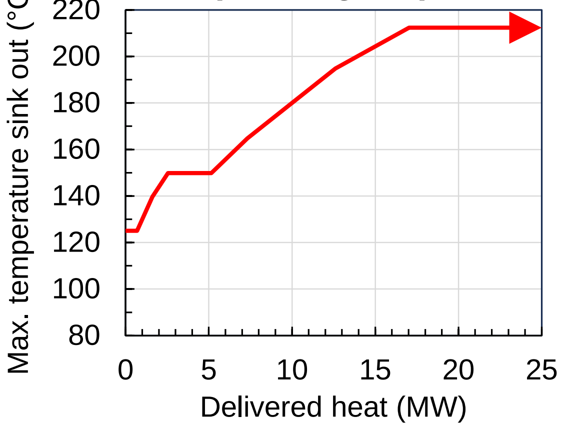
EPCON MVR-HP solutions

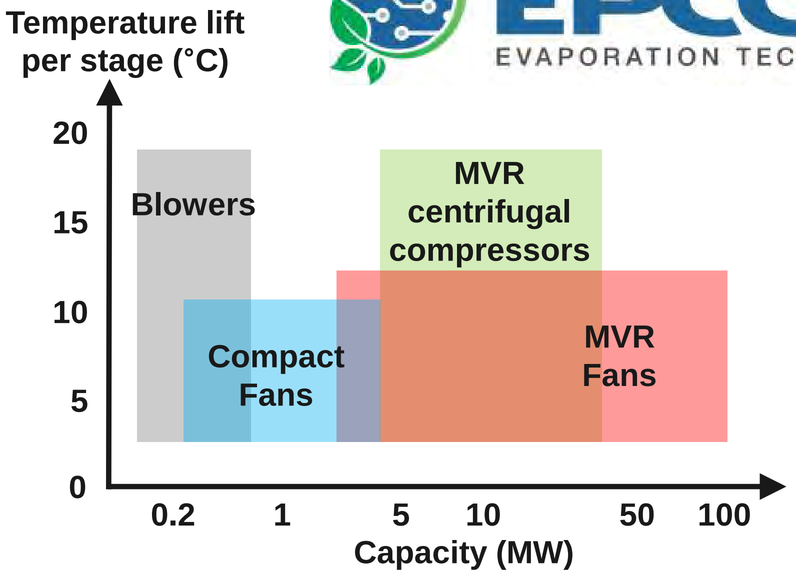
Wide temperature range with an optimized COP

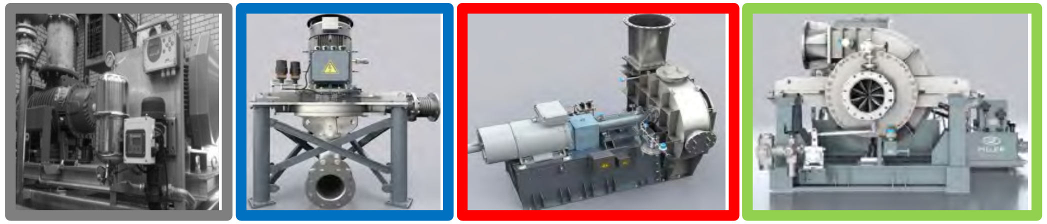
EPCON MVR-HP Obtainable COP



EPCON MVR-HP Operating map







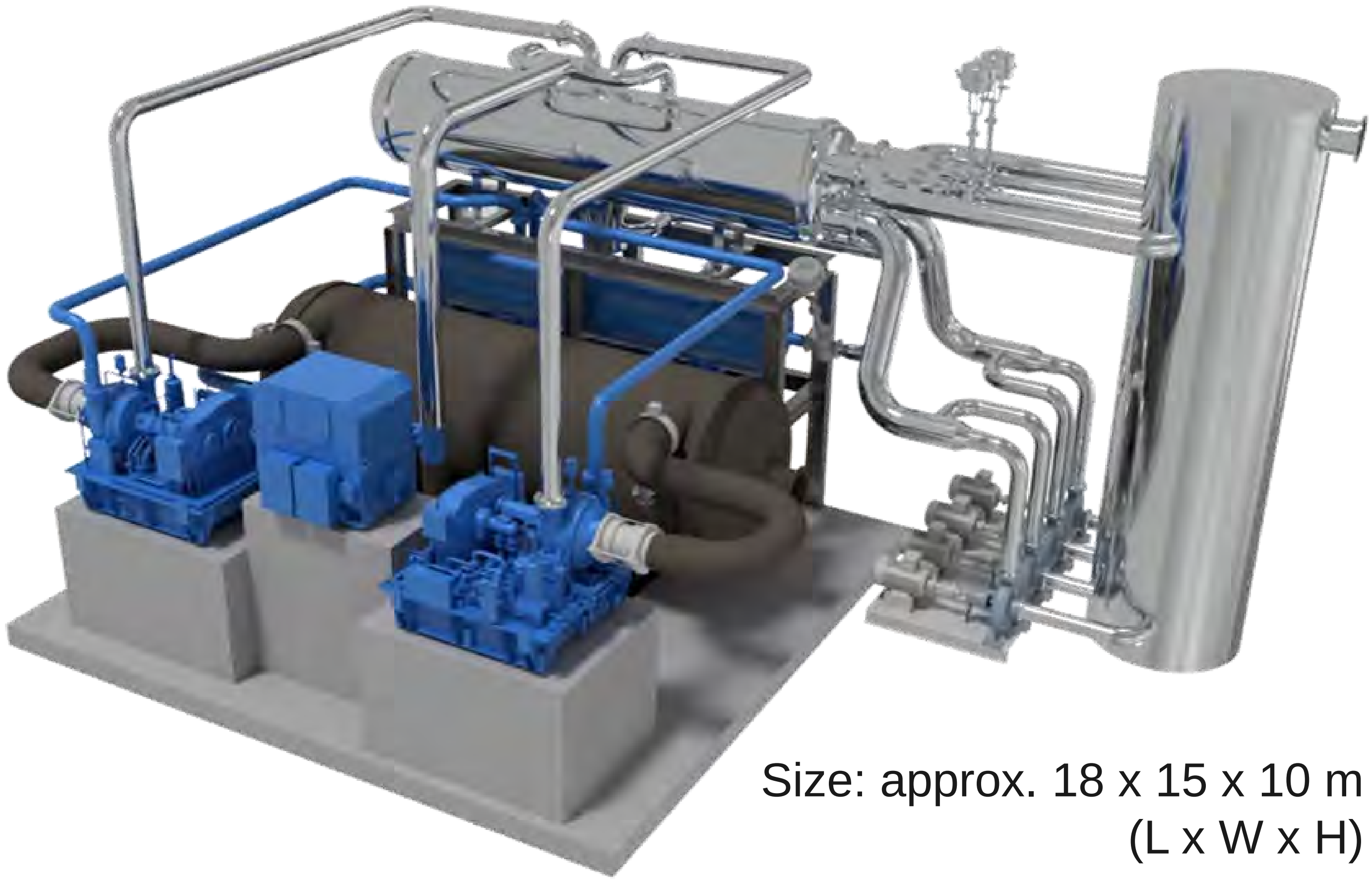
	Blowers	Compact Fans	MVR Fans	MVR centrifugal compressors
Capacity (kg/h)	150 to 5'000	200 to 5'000	3'000 to 250'000	5'000 to 55'000
Max. temp lift per stage (°C)	**15 to 20**	8 to 12	8 to 12	**15 to 20**
Footprint per stage (m2)	~1.5	~1.5	>2	>4
Max. suppy temperature (°C)	130	150	150	**200**
Internal efficiency (%)	**50**	75 to 85	75 to 85	75 to 85

Images courtesy by EPCON Evaporation Technology AS

Based on:
- EPCON (2022): 3rd HTHP Symposium 2022, 29-30 March 2022, Copenhagen
- EPCON (2024): 4th HTHP Symposium 2024, 23-24 January 2024, Copenhagen
- OST Webinar (2023) on Steam-Generating Heat Pumps

cordin.arpagaus@ost.ch

Large-Scale Steam Generation for the Industry



Size: approx. 18 x 15 x 10 m (L x W x H)

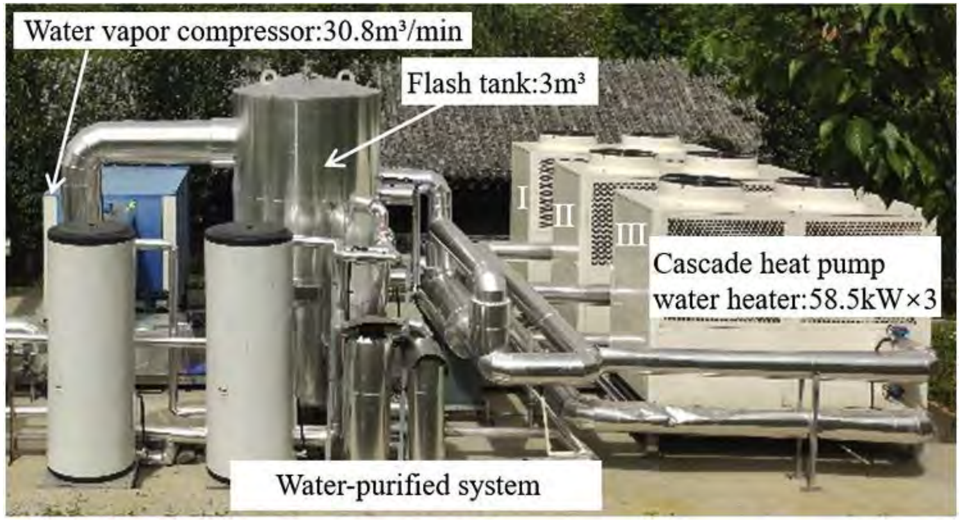
Image courtesy by Friotherm AG

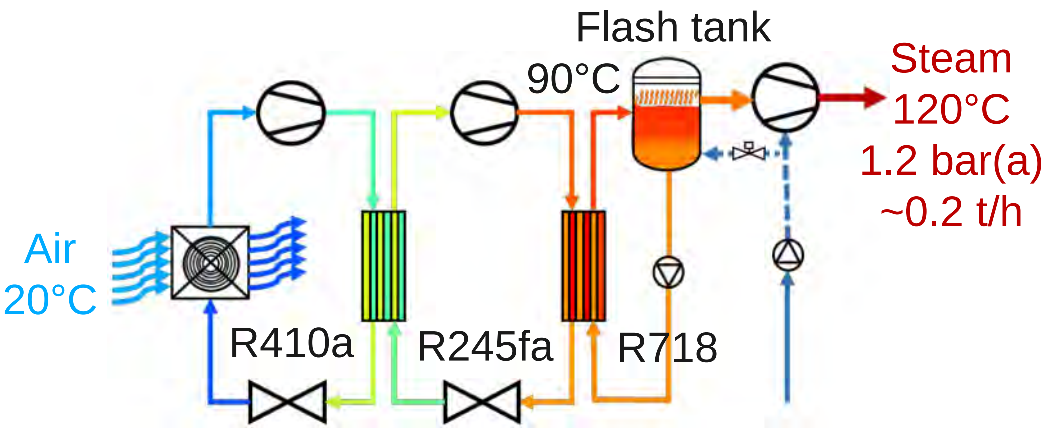
Parameter	Unit
Steam massflow	33 t/h
Steam temperature	130/137 °C
Steam pressure	3.3 bar(a)
Source temperature (in/out)	55/40 °C
Heat pump capacity	**25 MW_{th}**
COP	around 2.5
Refrigerant	R1233zd(E)

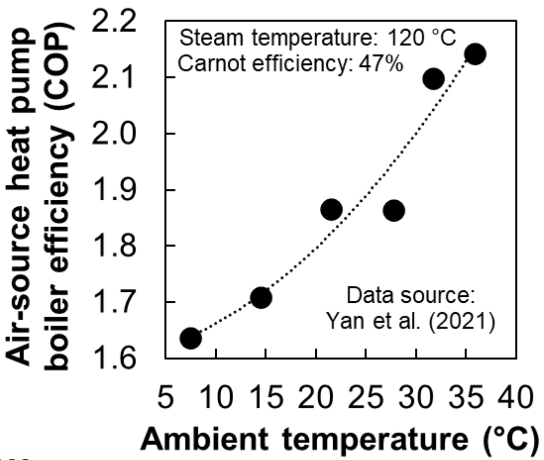
cordin.arpagaus@ost.ch

Hongjitang Brewery, Shandong, China

Air-source heat pump boiler in a brewing process in China







Installation	2019
Operating time	> 10’000 h
Refrigerants	R410a / R245fa / R718
Compressor	Twin-screw
Heat source	Air: 7 to 36 °C
Heat sink	Compressed steam: 120 °C
Heating capacity	180 kW (3 x 60 kW/unit)
COP	1.85 at 20 °C
Investment	RMB 1’116’000 (EUR 142’000)
Savings	Electricity 777’600 kWh/a RMB 467’000/a (EUR 59’000/a)
Payback	Around 2.4 years

Sources: IEA (2024): The Future of Heat Pumps in China
Yang L. (2023): IEA HPT Annex 58 HTHPs, 17th Status Meeting, 11-12 December 2023
Yan et al. (2021): Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2021.111026
Yan et al. (2020): Advances Sustainable Systems, https://doi.org/10.1002/adsu.202000118

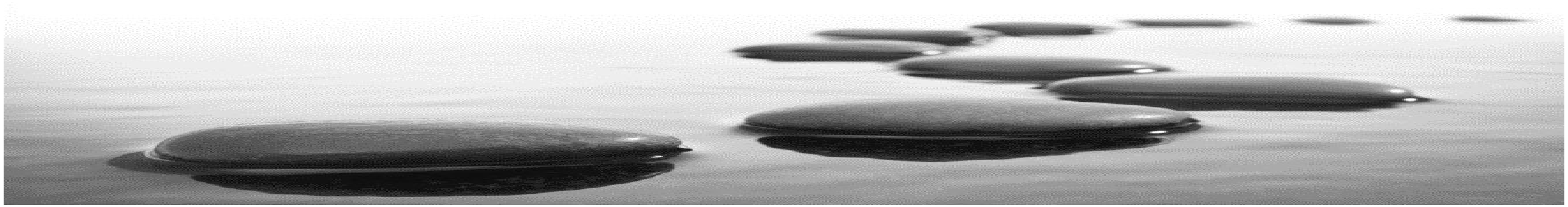
cordin.arpagaus@ost.ch

Three key recommendations for broader market adoption of high-temperature heat pumps

(1) **Better knowledge transfer (information sharing)** about capabilities, design, control, integration and suitable applications

(2) **A higher level of standardization** to reduce costs and planning efforts, resulting in more practical implementation examples (learn from experience, reduce implementation risks, and multiply application potential)

(3) **Create guidelines and train qualified personnel** able to implement industrial heat pumps optimally



Bertsch and Arpagaus (2023): High-temperature heat pumps are on the rise Why is their market uptake slow? HPT Magazine Vol.41 No 1/2023, https://heatpumpingtechnologies.org/column-high-temperature-heat-pumps-are-on-the-rise-why-is-their-market-uptake-slow/

cordin.arpagaus@ost.ch

Acknowledgments

sweet swiss energy research for the energy transition

DeCarbCH

DeCarbonisation of Cooling and Heating in Switzerland) (SI/502260) www.sweet-decarb.ch

Project: Annex 58 HTHP-CH
Integration of High-Temperature Heat Pumps (HTHPs) in Swiss Industrial Processes (SI/502336)

Push2Heat

Pushing forward the market potential of heat upgrading technologies in the industrial sector

Funded by the European Union

Grant Agreement No. 101069689
https://push2heat.eu

Project: IntSGHP
Integration of Steam-Generating Heat Pumps in Industrial Sites (Retrofit) (SI/502292)

IntSGHP

cordin.arpagaus@ost.ch

OST

Thank you for your attention !

OST
Eastern Switzerland
University of Applied Sciences

IES | Institute for Energy Systems

Dr. Cordin Arpagaus

OST – Eastern Switzerland
University of Applied Sciences
Institute for Energy Systems IES

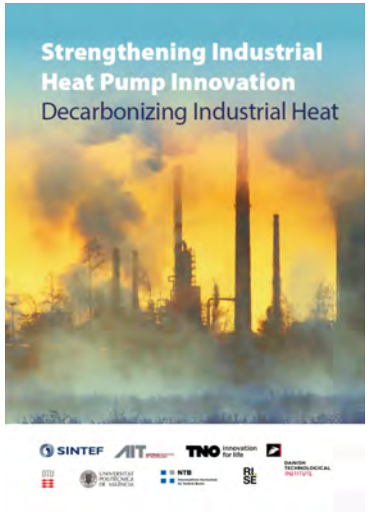
cordin.arpagaus@ost.ch
Tel. +41 58 257 34 94
www.ost.ch/ies

OST IES publications

Literature on Steam Generating Heat Pumps

STEAM

- **Arpagaus, C., Paranjape, S., Bless, F., Bertsch, S.S.,** Jansen, Ch.: Integration of a **steam-generating HTHP** in a Swiss meat factory, 4th HTHP Symposium, 23-24 January 2024, Copenhagen, Denmark https://www.hthp-symposium.org/hthp-symposium-2024
- **Arpagaus, C.; Bless, F.; Bertsch, S.**: Techno-Economic Analysis of **Steam-Generating Heat Pumps** in Distillation Processes, 3rd High-Temperature Heat Pump Symposium 2022, 29-30 March **2022**, Copenhagen, Denmark, https://hthp-symposium.org
- **Arpagaus, C., Bless, F., Bertsch, S.**: Techno-economic analysis of **steam generating heat pumps** for integration into distillation processes, GL2022, 15th IIR-Gustav Lorentzen conference on Natural Refrigerants, June 13-15, **2022**, Trondheim, Norway, http://dx.doi.org/10.18462/iir.gl2022.0029
- **Arpagaus, C.**: High Temperature Heat Pumps – Market Overview, Refrigerants, Application Examples in Food Industry, and **Steam Generation Heat Pumps**, A2EP Briefing: Advances in industrial heat pumps, Australian Alliance for Energy Productivity, 3 September **2020** (Video Recording of Webinar)
- **Bless, F.; Arpagaus, C.; Bertsch, S.**: Theoretical Investigation of High-Temperature Heat Pump Cycles for **Steam Generation**, 13th IEA Heat Pump Conference, Jeju, Korea, 26 -29 April **2021**
- **Bless, F., Arpagaus, C., Bertsch, S.S.**, Schiffmann, J., Theoretical analysis of **steam generation methods** – the case of high temperature heat pump, The Seventh International Symposium on Energy (Energy7), Manchester, UK, 13-17 August **2017**
- **Bless, F., Bertsch, S., Arpagaus, C.**, Schiffmann, J., 2016, Theoretical analysis of **steam generation methods** – Energy, CO_2 emission and cost analysis, Industrial Efficiency ECEE Conference, Berlin, 12-15 September **2016**
- **Bless, F., Arpagaus, C., Bertsch, S.S.**, Schiffmann, J.: Theoretical analysis of **steam generation methods** - Energy, CO_2 emission, and cost analysis, Energy, **2017**, 129, 114-121, https://doi.org/10.1016/j.energy.2017.04.088
- **Paranjape, S., Arpagaus, C., Bless, F., Bertsch, S.**: **Steam Generating Heat Pumps** for Process Heating in Agro Food Sector, Session IV, Application of Heat Pumps in Food Processing Industries, REFCOLD India, Chennai Trade Centre, 13 October **2023**
- Payá, J., Cazorla-Marín, A., Hassan, A.H., **Arpagaus, C.:** Techno-economic evaluation of different technologies to produce **steam** at 150 ºC in the Spanish industry, 12th CNIT, XII National and y III International Conference on Engineering Thermodynamics, June 29 - July 1, **2022**, Madrid, Spain
- Saini, P., Hedstrom, A., **Arpagaus, C., Bless, F., Bertsch, S.**: A hybrid system of **steam generating heat pump** and solar parabolic trough collectors for process heating: Techno-economic analysis for a brewery, 3rd High-Temperature Heat Pump Symposium 2022, 29-30 March **2022**, Copenhagen, Denmark, https://hthp-symposium.org
- **Uhlmann, M.**, Olmedo, L.E., **Arpagaus, C., Bless, F.**, Schiffmann, J., **Bertsch, S.**: Efficient **steam generation** in industry – Combined heat pump cycle with mechanical vapor recompression, 15th IIR-Gustav Lorentzen conference on Natural Refrigerants, 13-15 June **2022**, Trondheim, Norway, http://dx.doi.org/10.18462/iir.gl2022.0049
- Saini, P., Ghasemi, M., **Arpagaus, C., Bless, F., Bertsch, S.**, Zhang, X.: Techno-economic comparative analysis of solar thermal collectors and high-temperature heat pumps for industrial **steam generation**, Energy Conversion and Management, Volume 277, 1 February **2023**, 116623, https://doi.org/10.1016/j.enconman.2022.116623
- Wördemann, M., **Arpagaus, C., Bertsch, S.S.**, Thomas, Ch.: Design options of HTHP technology in comparison to existing industrial **steam** boiler systems, 4th HTHP Symposium, 23-24 January 2024, Copenhagen, Denmark, https://www.hthp-symposium.org/hthp-symposium-2024



cordin.arpagaus@ost.ch

OST

OST IES publications

Literature References 2020 to 2022

- **Arpagaus, C.; Bless, F.; Bertsch, S.:** Techno-Economic Analysis of Steam-Generating Heat Pumps in Distillation Processes, 3rd High-Temperature Heat Pump Symposium 2022, 29-30 March 2022, Copenhagen, Denmark
- Mateu-Royo, C.; **Arpagaus, C.;** Mota-Babiloni, A.; Navarro-Esbrí, J.; **Bertsch, S.:** Advanced High Temperature Heat Pump Configurations using low GWP Refrigerants for Industrial Waste Heat Recovery: A Comprehensive Study, Energy Conversion and Management, Vol. 229, 1 February 2021, 113752, https://doi.org/10.1016/j.enconman.2020.113752
- Kosmadakis, G.; **Arpagaus, C.;** Neofytou, P.; **Bertsch, S.:** Techno-Economic Analysis of High-Temperature Heat Pumps with low-GWP Refrigerants for upgrading Waste Heat up to 150 °C, Energy Conversion and Management, Vol. 226, 113488, pp. 1-19, https://doi.org/10.1016/j.enconman.2020.113488
- Schiffmann, J.; Kontomaris, K.; **Arpagaus, C.; Bless, F.; Bertsch, S.:** Scale Limitations of Gas Bearing Supported Turbocompressors for Vapor Compression Cycles, International Journal of Refrigeration, Vol. 109, pp. 92-104, 2020, https://doi.org/10.1016/j.ijrefrig.2019.09.019
- Schlosser, F.; Jesper, M.; Vogelsang, J.; Walmsley, T.G.; **Arpagaus, C.;** Hesselbach, J.: Large-Scale Heat Pumps: Applications, Performance, Economic Feasibility and Industrial integration, Renewable and Sustainable Energy Reviews, Vol. 133, 1102019, pp. 1-20, 2020, https://doi.org/10.1016/j.rser.2020.110219
- **Arpagaus, C.; Bertsch, S.:** Industrial Heat Pumps in Switzerland – Application Potentials and Case Studies, Final Report, on behalf of the Swiss Federal Office of Energy, SFOE contract number: SI/501782-01, Bern, 23 July 2020.
- De Boer, R.; Marina, A.; Zühlsdorf, B.; **Arpagaus, C.**; Bantle, M.; Wilk, V.; Elmegaard, B.; Corberán, J.; Benson, J.: Strengthening Industrial Heat Pump Innovation, Decarbonizing Industrial Heat, White Paper, 14 July 2020.
- **Arpagaus, C.; Bertsch, S.:** Experimental Comparison of R1224yd(Z) and R1233zd(E) in a High Temperature Heat Pump, 13th IEA Heat Pump Conference, Jeju, Korea, 26-29 April 2021.
- **Arpagaus, C.; Bertsch, S.:** Successful Application Examples of Industrial Heat Pumps in Switzerland, IIR International Rankine 2020 Conference, 27-31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1183
- **Arpagaus, C.; Bertsch, S.:** Experimental Comparison of HCFO R1233zd(E) and R1224yd(Z) in a High Temperature Heat Pump up to 150 °C, IIR International Rankine 2020 Conference, 27 to 31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1129
- **Arpagaus, C.; Bertsch, S.:** Experimental Comparison of HCFO and HFO R1224yd(Z), R1233zd(E), R1336mzz(Z), and HFC R245fa in a High Temperature Heat Pump up to 150 °C Supply Temperature, 18th International Refrigeration and Air Conditioning Conference at Purdue, 23-27 May 2021. https://docs.lib.purdue.edu/iracc/2200
- **Arpagaus, C.; Bless, F.; Bertsch, S.:** Theoretical Analysis of Transcritical HTHP Cycles with low GWP HFO Refrigerants and Hydrocarbons for Process Heat Applications up to 200 °C, IIR International Rankine 2020 Conference, 27-31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1168
- **Bless, F.; Arpagaus, C.; Bertsch, S.:** Theoretical Investigation of High-Temperature Heat Pump Cycles for Steam Generation, 13th IEA Heat Pump Conference, Jeju, Korea, 26 -29 April 2021.
- **Arpagaus, C.; Bless, F.; Bertsch, S.:** Theoretical Analysis of Transcritical HTHP Cycles with low GWP HFO Refrigerants and Hydrocarbons for Process Heat Applications up to 200 °C, IIR International Rankine 2020 Conference, 27 to 31 July 2020, Glasgow, UK, http://dx.doi.org/10.18462/iir.rankine.2020.1168
- Diewald, K; **Arpagaus, C.**; Hebenstreit, B.: Thermodynamic Analysis of low GWP HFO and HCFO Refrigerants in HTHP with Large Temperature Glides on the Heat Sink, IIR International Rankine 2020 Conference, 27-31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1166

cordin.arpagaus@ost.ch